

**CONCEPTUAL STUDY
OF
ARTICULATED STABLE OCEAN PLATFORM**

**FINAL REPORT
PART I**

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| 19. ABSTRACT (Continue on reverse if necessary and identify by block number) A conceptual study has been completed to evaluate the feasibility of a new concept of a floating storage platform - the Articulated Stable Ocean Platform (ASOP). The unique aspects of the ASOP is the articulation of the stabilize buoys which were introduced for the purposes of reducing wave load and overall vessel motion. The ASOP was designed to have a fuel storage capability of 1 million barrels and to support a topside up to 12,000 kips in total weight. The fuel storage tanks were designed in such a way that the draft of the platform would remain unchanged at any loading condition without adjusting the ballast. This greatly simplified the operations and allowed the platform to continue other activities while loading and off-loading. | | | |
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The study shows that the ASOP has adequate stability and satisfies the stability requirement of the certifying authorities. Both numerical analysis and model test showed that the ASOP offers exceptional motion response characteristics in all its degrees of freedom. In terms of platform motion response, the ASOP is capable of operating in more severe weather conditions than a conventional surface vessel type platform. A seven body (six buoys and the hull) coupled motion analysis in ocean environment was performed and results in general agreed with the model test. However, both numerical analysis and model tests showed that the articulated buoys have no clear advantage over fixed buoys in the global motion of the ASOP. The reduction of forces by using articulation did not significantly improve the motion of the platform. Furthermore, the analysis and model test showed that compared to the fixed buoy case, using articulations increased the slow drift motions of the ASOP in random waves. The study also indicated that the introduction of articulations complicated the hydrostatic stability of the platform. Damaged stability was the governing factor in determination of the size of the articulated buoys. In conclusion, this conceptual study indicated that the fuel storage ASOP is a viable concept. Its large storage capability and exceptional motion characteristics allow many applications both in civil and military purpose.

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CHAPTER 1 INTRODUCTION

1.1 General

The Articulated Stable Ocean Platform (ASOP) is a new concept of floating storage offshore platform. It consists of the following basic components:

- 1) A hexagonal shape hull submerged in the water for fuel storage and ballast water;
- 2) Six surface-piercing buoys provide the stability for the platform. The buoys are cylindrical shaped and are attached to each corner of the hexagonal hull by means of universal joints;
- 3) A topside platform which houses the prime movers, pumps, mooring machinery, handling equipment and the payload supports, etc.;
- 4) A column located at the center of the hull supporting the topside. It also provides access to the lower hull and serves as an enclosure for piping, machinery, hawser pipes, etc.

Figure 1.1 shows the general arrangement of the ASOP. During deployment, the ASOP is towed to the site with its hull floating on the surface. The articulated buoys are secured in a horizontal position on the top of the hull. Upon arrival in the designated area, the ASOP is moored in a six-point mooring system. The articulated columns are rendered operable and the tanks in the hull are flooded to submerge the main hull to its prescribed draft. The buoys provide stability during the submerging evolution.

The ASOP has a geometry that is substantially different from the conventional ship, or other monohull platforms, such as FPSO (Floating Production, Storage and Off loading Platform). The geometry leads to hydrostatic and hydrodynamic behavior that is significantly different in its principles of operation. Because a large proportion of its submerged volume (hull) is at a deep draught where dynamic pressures have rapidly decayed with depth, the ASOP possesses low wave-induced motions. The small water plane area and the large submerged volume of the platform yield long natural periods in heave, roll and pitch. These periods are well above the periods of predominant wave action, further contributing to a reduction of

the motion. By using articulation and allowing the buoys to rotate in pitch and roll, forces and motions transmitted from the buoys to the hull are minimized. Therefore, the ASOP is a "stable" platform and is suitable for the offshore tasks which have high restrictions on motion, such as offshore oil drilling and production, fuel storage, or military use.

In addition to the favorable motion characteristics, the ASOP has other advantages over conventional floating vessel production units. The advantages are as follows:

- 1) Production and integral oil storage in the same unit; no need for pipelines, storage tankers, and associated single point moorings.
- 2) A specific water depth is not required other than the requirement that the water be sufficiently deep to preclude grounding.
- 3) Mobile - can be moved as required with minimum effort.
- 4) Accommodates deck loads as required for oil production and storage or others by varying structural dimensions.
- 5) Fuel storage is sufficiently deep to preclude danger of tank rupture and oil spillage from collision damage.

1.2 Scope of Work

In this conceptual study of the ASOP, our objective was to produce a conceptual design and evaluate this design by a combination of analytical engineering and physical model tank testing. The fundamental issues were to determine the overall motion of the vessel and the interaction behavior of the articulated buoys and hence prove the viability and benefits of the ASOP. The study included the following tasks:

- 1) Application investigation and hull configuration design
- 2) Hull scantlings and weight estimate
- 3) Verify intact and damage stability
- 4) Seakeeping analysis
- 5) Model test
- 6) Cost estimate

All the procedures and results of the analysis for the above tasks are documented in this report. The report consists of two parts. Part I includes the design and numerical analysis, and summary of model test results. Part II includes detailed model test description and test results.

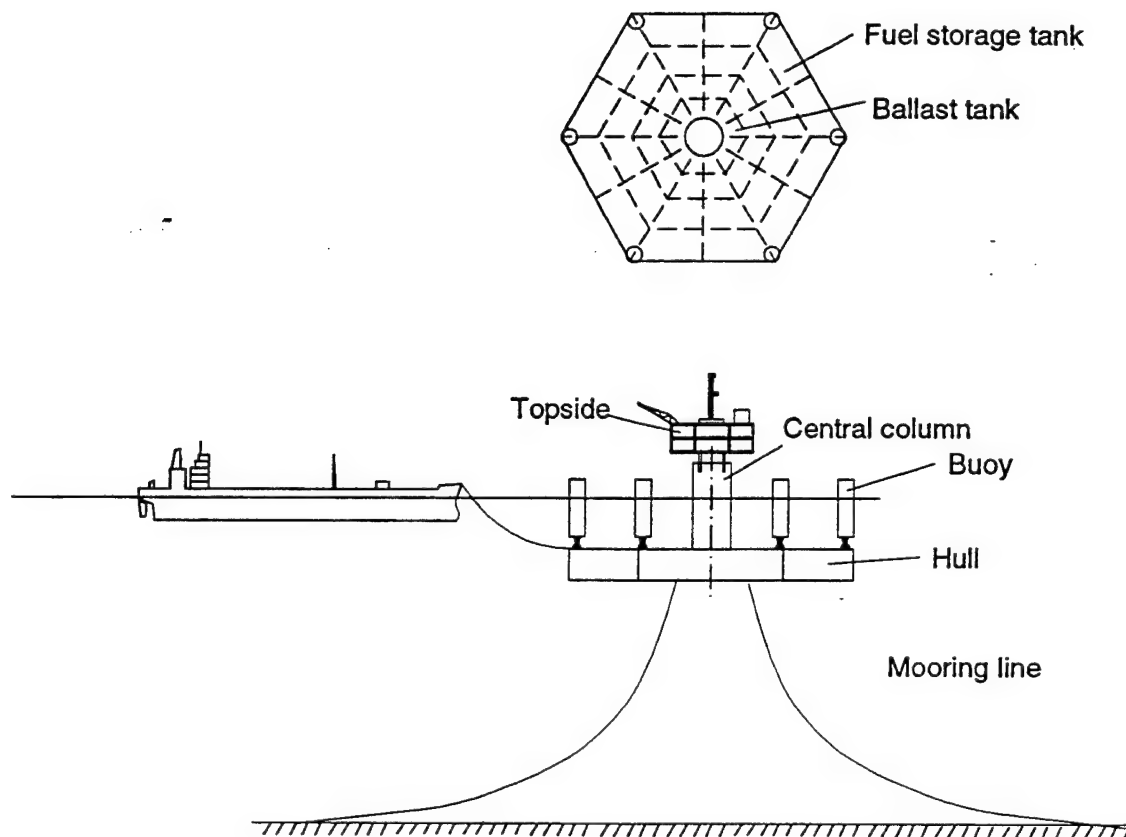


Figure 1.1 Articulated Stable Ocean Platform (ASOP)

CHAPTER 2 HULL CONFIGURATION

2.1 General

In this conceptual study stage, the military usage of the platform is not clear except for serving as a fuel storage and off-loading vessel, in which the topside hosts only fuel pumping equipment and has a small payload. Other applications of the platform may require higher payload on the topside. In this chapter, the configuration of the ASOP is determined based on its application in the offshore oil industry. The ASOP serves as an offshore oil production and fuel storage platform with a storage capacity of one million barrels. Figure 2.1 shows the configuration of the ASOP. The following sections describe the configuration design of the major components of the ASOP.

2.2 Topside

The topside weight may vary significantly depending on the applications and functions of the ASOP. It is the key factor to the stability of the platform due to its high level and it determines the configuration of hull and buoys. In this study, we estimated the topside and payload of the ASOP as an offshore fuel storage and production platform. The total weight of the topside is 12,000 kips, which includes the deck structural weight (2340 kips), fuel off-loading facilities, production and drill equipment and facilities (9660 kips). The center of gravity of the topside is 100 ft above waterline at the operational draft.

2.3 Hull

The total volume of the hull is determined by the fuel storage capacity and required ballast water. In our design, the hull has a hexagonal shape for simplicity. The hull height is 50 ft, and the distance across corners is 450 ft. The bottom of the hull is 145 ft below waterline. The tanks in the hull are divided into four ring shaped groups by four concentric hexagonal bulkheads. In each group, there are twelve tanks which are divided by the radial bulkheads. Figure 2.2 shows the dimension and compartmentation of the hull. The outer two groups of tanks are pressure compensated soft storage tanks, the "soft" means the structure of these tanks are not

designed to take high hydrostatic pressure. The third group of tanks which is next to the soft tanks is pressure uncompensated hard storage tanks. The inner group of tanks is ballast tanks. The volume of the tanks is as follows:

| Group | Volume (ft ³) |
|--------------|---------------------------|
| Soft tank 1 | 2.82×10^6 |
| Soft tank 2 | 2.04×10^6 |
| Hard tank | 8.87×10^5 |
| Ballast tank | 6.90×10^5 |

The total capacity of fuel storage is 5.63×10^6 cubic feet, or about 1 million barrels. The total capacity of variable water ballast is 4.42×10^5 kips. When the platform needs to be relocated, the ballast water is pumped out to raise the hull near the water surface so that the soft tanks can be emptied at low pressure for transition. Unlike a tanker which has large variations of draft at different loading conditions due to the fuel weight change, the ASOP is designed to keep the operational draft at all loading conditions. In order to do so, the volume ratio of the soft tanks to hard tanks is designed to be 1 to 0.18. During loading (off-loading), the change of weight due to one barrel of fuel (water) displacing a like volume of sea water (fuel) in the soft tanks can be compensated by pumping 0.18 barrel fuel into (out of) the hard tanks displacing (replaced by) only air at the same time. Therefore, at any fuel loading condition, the total weight of the fluid (fuel and water) in the storage tanks is unchanged if the same 1 to 0.18 pumping ratio is maintained. The overall changes in the weight of the platform are handled by changing the amount of water in variable ballast tanks.

One of the concerns in the compartmentation of the hull is stability. In our design, the hull is compartmentalized in a way such that, when any one of the tanks in the hull is flooded, the platform will remain afloat with the topside above the water surface. The most severe situation is the flooding of one of the outmost soft tanks which is full of fuel. The gain of weight (2256 kips) by replacing fuel with sea water is not of serious concern, but the overturning moment created by the weight increase can cause a large heel. The damaged stability is further explained in Chapter 4.

2.4 Center Column

The center column is a cylindrical structure which is 60 ft in diameter and 150 ft long. The column has a free board of 55 ft at operational draft. The deck, which is mounted on the top of the center column, has a 70 ft air gap (vertical distance between waterline and the lowest deck structure) to avoid wave impact in a severe environmental condition. The column provides access to the lower hull and serves as an enclosure for piping and machinery, and more important, provides water plane area and reserved buoyancy for the stability of the platform. Figure 2.3 shows the dimensions and compartmentation of the center column.

2.5 Buoys

The six articulated buoys are cylindrical shaped and 30 ft in diameter and 85 ft long. The design draft of the buoys is 55 ft. Each buoy is located at the corner of the hexagonal hull to maximize the righting moment arm. At operational draft, the buoy has a net buoyancy of 1636 kips. At transit draft, the buoys are secured horizontally on top of the hull. Figure 2.4 shows the dimension and compartmentation of the buoy. The two radial bulkheads and two flats divide the buoys into 12 watertight compartments and limit the flooding volume when the buoy is damaged. Our damage stability analysis (in Chapter 4) indicates that flooding of four compartments at the same time will not jeopardize the platform.

2.6 Summary

The following are the principal characteristics of the ASOP:

| | | |
|--------------------------------|-----|----|
| Hull diameter (across corners) | 450 | ft |
| Hull height | 50 | ft |
| Center column diameter | 60 | ft |
| Center column height | 150 | ft |
| Buoy diameter | 30 | ft |
| Buoy length | 85 | ft |
| Transit draft | 35 | ft |
| Operational draft | 145 | ft |

| | | |
|----------------------------|---------|----------------|
| Buoy draft (operational) | 55 | ft |
| Topside weight | 12,000 | kip |
| Topside C.G. | 245 | ft above keel |
| Fuel storage | 1 | million barrel |
| Ballast water | 442,000 | kip |
| Displacement (transit) | 294,622 | kip |
| Displacement (operational) | 452,865 | kip |

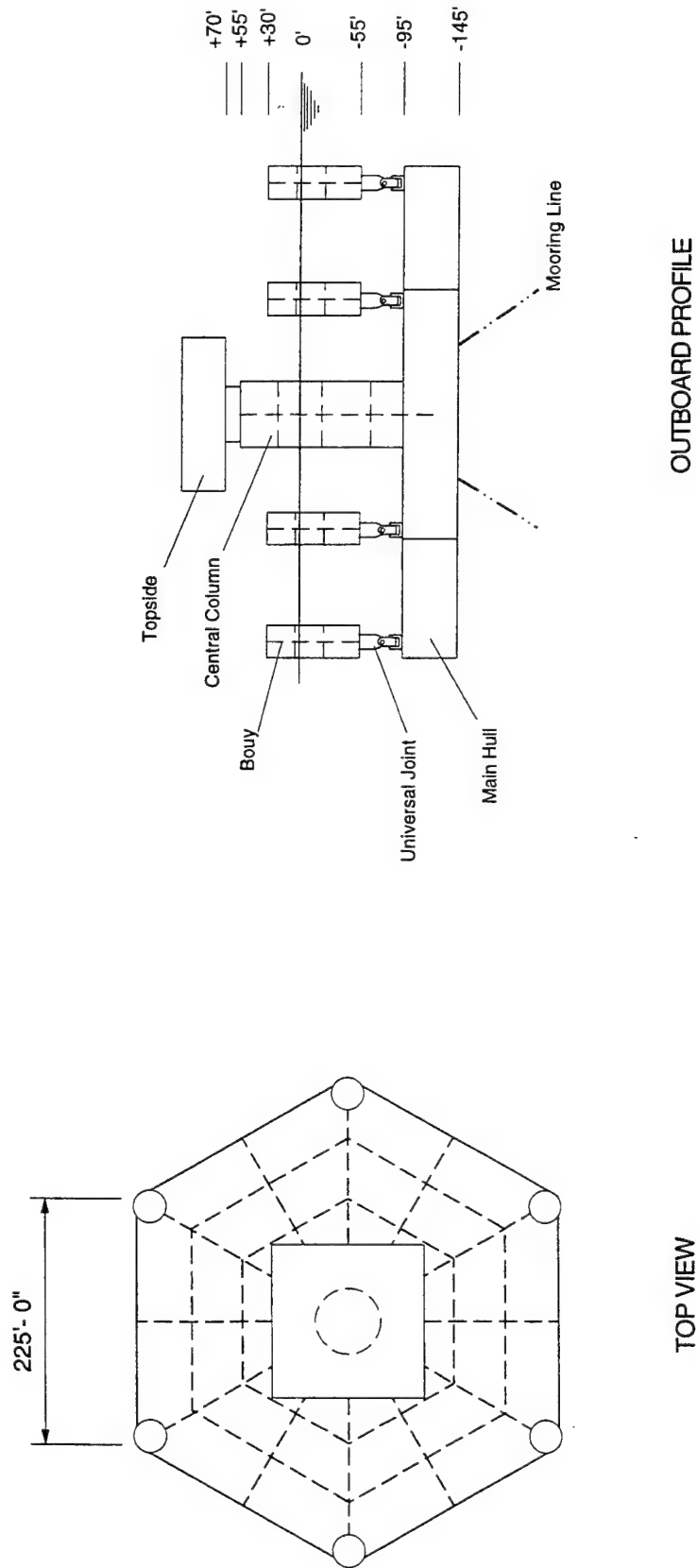


Figure 2.1 General arrangement of the ASOP

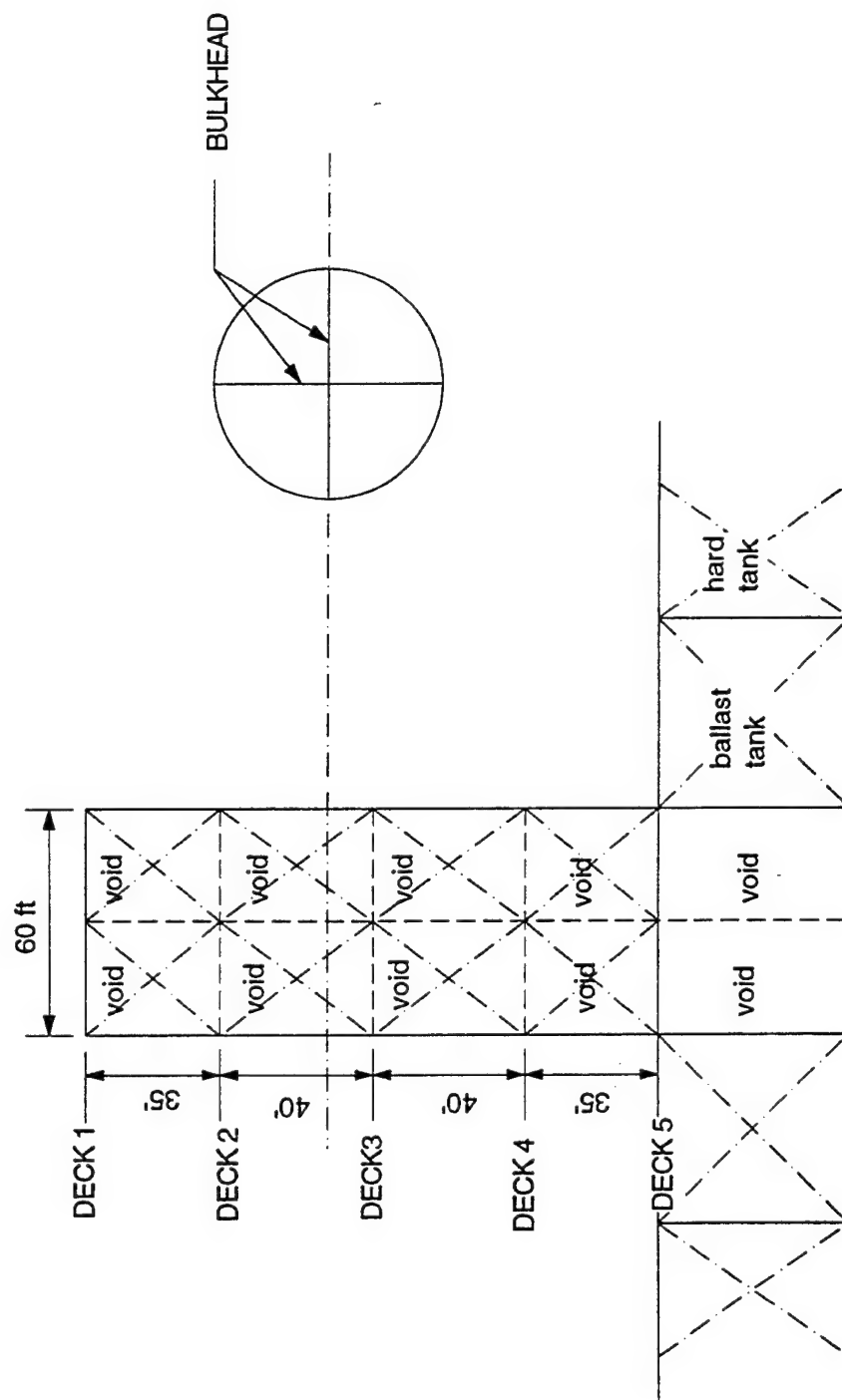


Figure 2.3 Compartmentation of the center column

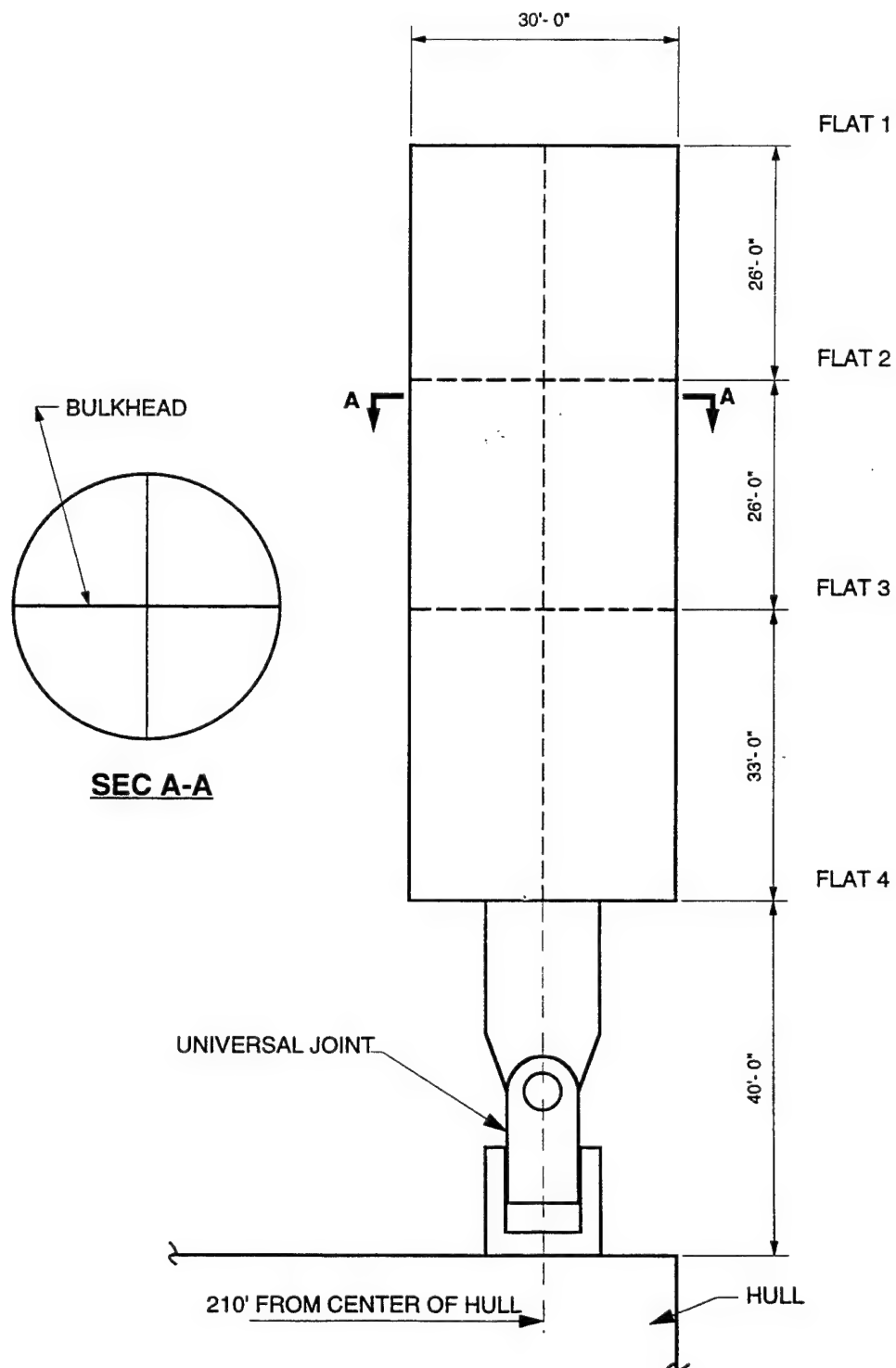


Figure 2.4 Compartmentation of the buoy

CHAPTER 3 HULL SCANTLING AND WEIGHT ESTIMATE

3.1 Structural Scantling

The structural scantlings of the ASOP are based on the Rules for Building and Classing Mobile Offshore Drilling Units and the rules of the American Bureau of Shipping (ABS), Section 5 -- Column-stabilized Drilling Units. The objective of the scantling is to design a preliminary structural arrangement, determine the dimensions of the structural components, and to provide a base for the steel weight estimation. In the scantling, the major structural components, such as shell plate, bulkhead plate, beam, girder, frame and stiffener are determined. Smaller members, such as brackets, stiffeners on the web plate of the girders, and tripping brackets supporting the face plate of the girder, were not designed; however, there are many of those members and their total weight is still significant. The weight of these members is approximated by a percentage of the main structure they attached to. For example, the weight of the stiffeners and tripping brackets on the girder is approximated to be 20 percent of the total weight of the girder. In the scantling, the structural arrangement is not optimized and the size of the members is conservative. Although we considered hydrostatic pressure force as the only external force during the design, the wave induced force is included in an indirect way by using a maximum draft of 165 ft (design draft + 20 ft) for hydrostatic pressure calculations. Figures 3.1 to 3.12 shows the structural arrangement and dimensions of the ASOP hull and buoys. Tables 3.1 to 3.9 show the structural design according to the ABS rules.

3.2 Weight Estimate

The structural weight, outfittings and fixed payload for the ASOP are shown in Table 3.10. The steel weights of the hull and the buoys are based upon the structural scantling. A 20 percent margin is added to the total steel weight of the hull. At this conceptual study stage, the functions of the topside are not totally defined except fuel loading and off-loading, hence the weight of the equipment and payloads on the top side is not definite. Therefore, a total topside weight of 12,000 kips is used in the weight estimation.

3.2.1 Operational

Tabel 3.11 shows the loads at the operational draft of 145 ft. The maximum fuel storage capability is 1 million barrels. As we mentioned earlier, by pumping at a certain ratio simultaneously from the soft tanks and the hard tanks during loading and off-loading, the total weight of fluid in the storage tanks will remain unchanged. The change of variable payload can be easily adjusted by controlling ballast water. The location of the center of gravity (C.G.) and radius of gyration of the platform and buoys are also computed for the stability analysis, motion analysis, and model test (see Chapters 4, 5 and 6).

3.2.2 Transit Draft

During transit there is no fuel stored in the platform. Eight of the twelve small soft tanks will be filled 100 percent with ballast water together with ballast tanks to keep the platform at a draft of 35 ft. The rest of the storage tanks are empty. The buoys are positioned and secured horizontally on the top of the hull and become a fixed load. All the mooring lines and anchors are onboard. Table 3.12 shows the loading conditions for the transit mode.

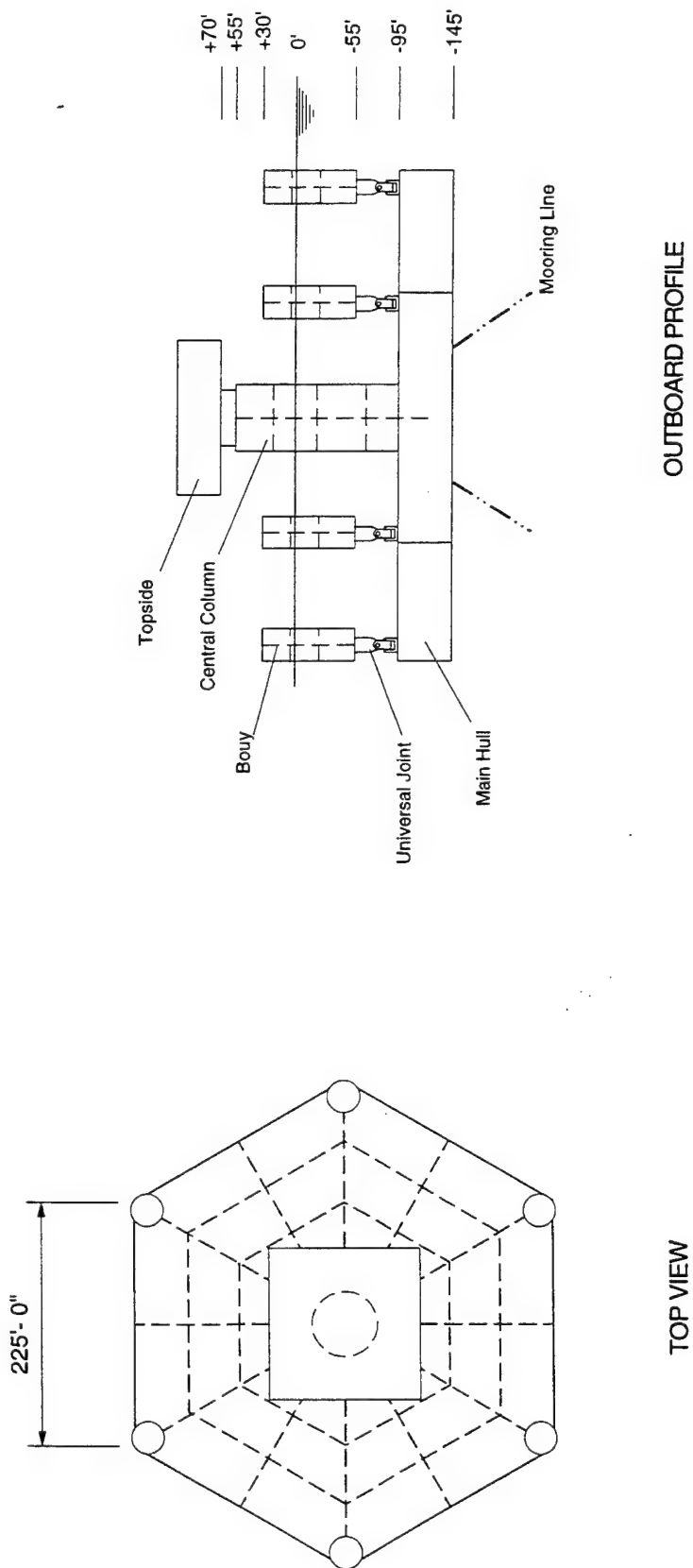


Figure 3.1 General arrangement of the ASOP

| | STIFFENER | GIRDER | PLATE THICKNESS |
|--------------|------------|-----------------|-----------------|
| SOFT TANK 1 | L8x4x1 3/4 | 70x3/4x20x1 1/4 | 3/4" |
| SOFT TANK 2 | L8x4x1 3/4 | 70x3/4x20x1 1/4 | 3/4" |
| HARD TANK | L8x6x1 | 55x3/4x18x1 | 1" |
| BALLAST TANK | L8x6x1 | 70x3/4x18x1 | 1" |

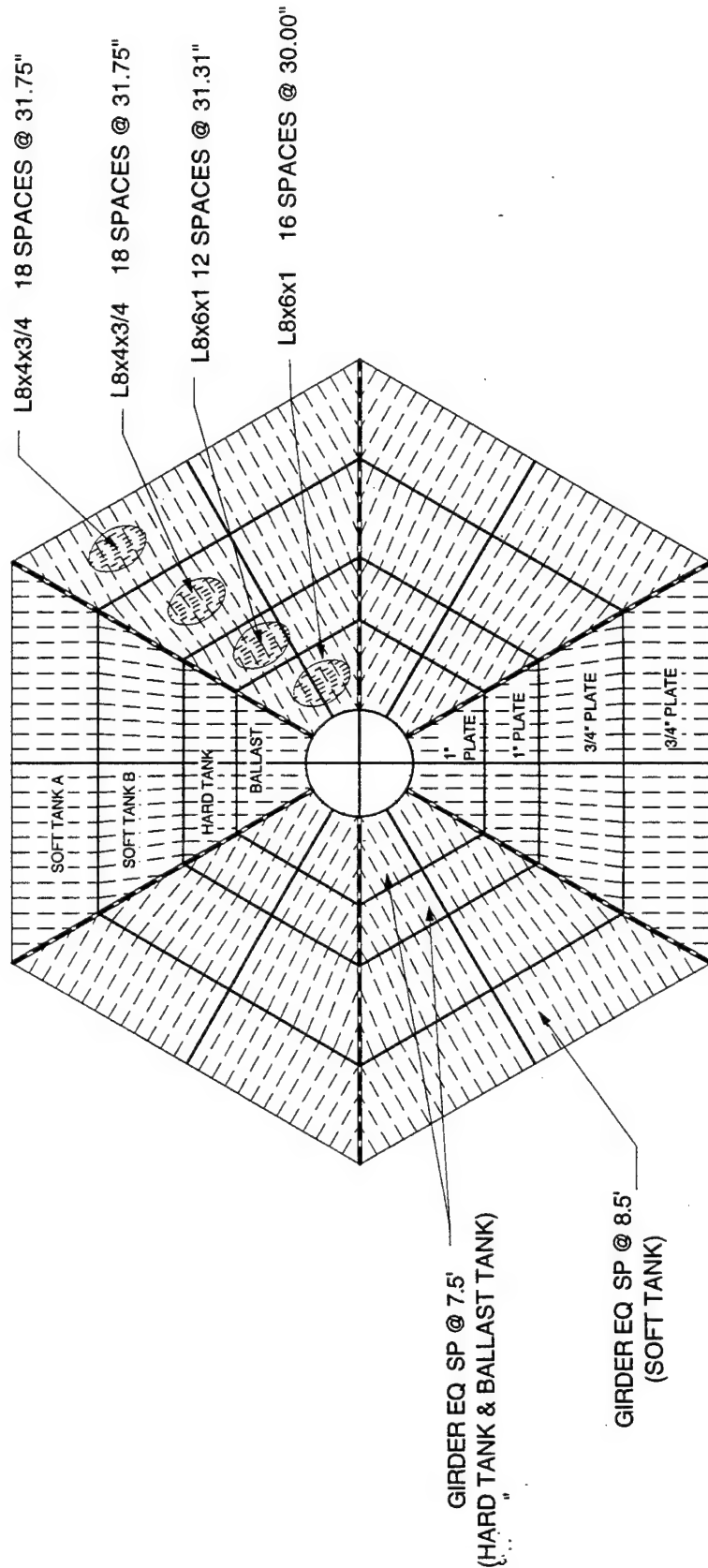


Figure 3.2 The ASOP hull top plate framing

| | STIFFENER | GIRDER | PLATE THICKNESS |
|--------------|------------|-----------------|-----------------|
| SOFT TANK 1 | L8x4x1 3/4 | 70x3/4x20x1 1/4 | 3/4" |
| SOFT TANK 2 | L8x4x1 3/4 | 70x3/4x20x1 1/4 | 3/4" |
| HARD TANK | L9x6x1 1/8 | 55x3/4x18x1 | 1" |
| BALLAST TANK | L9x6x1 1/8 | 82x1x22x1 3/8 | 1" |

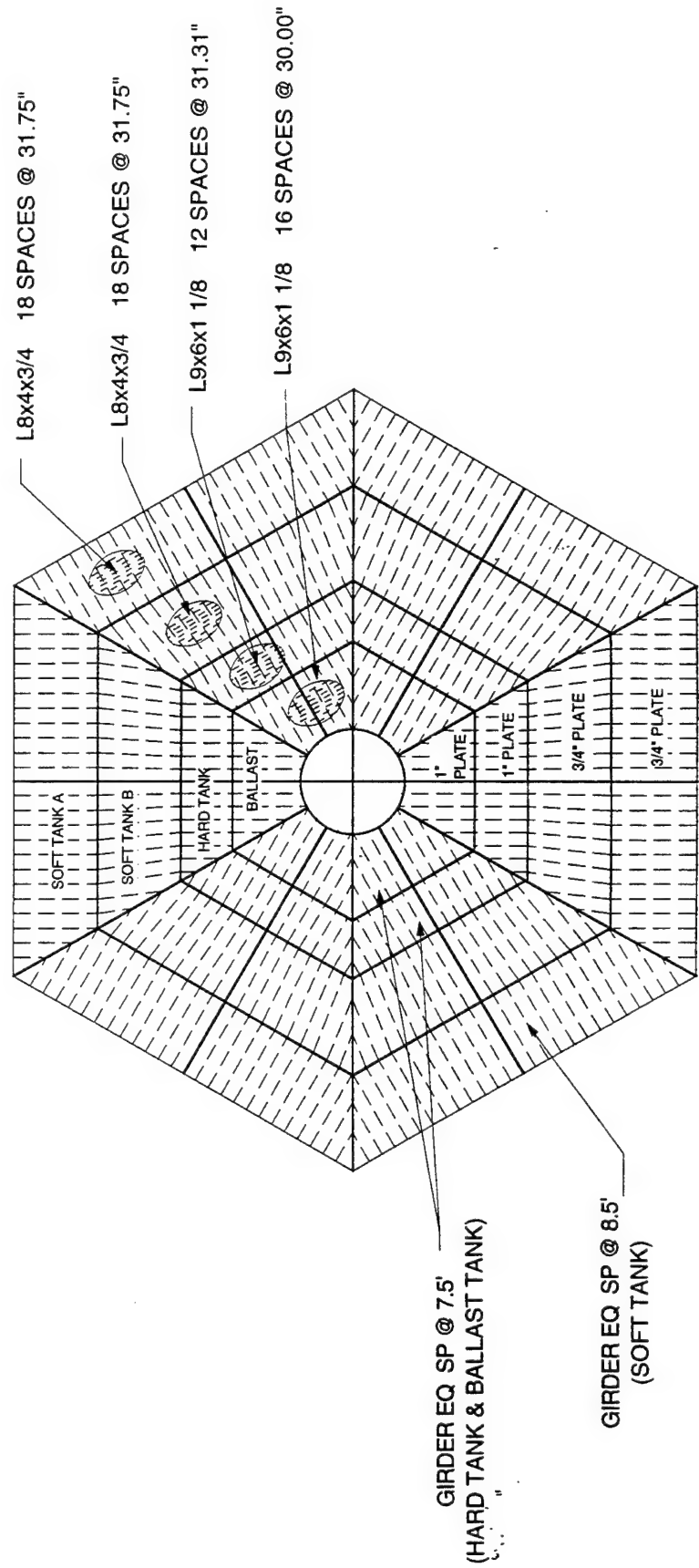


Figure 3.3 The ASOP hull bottom plate framing

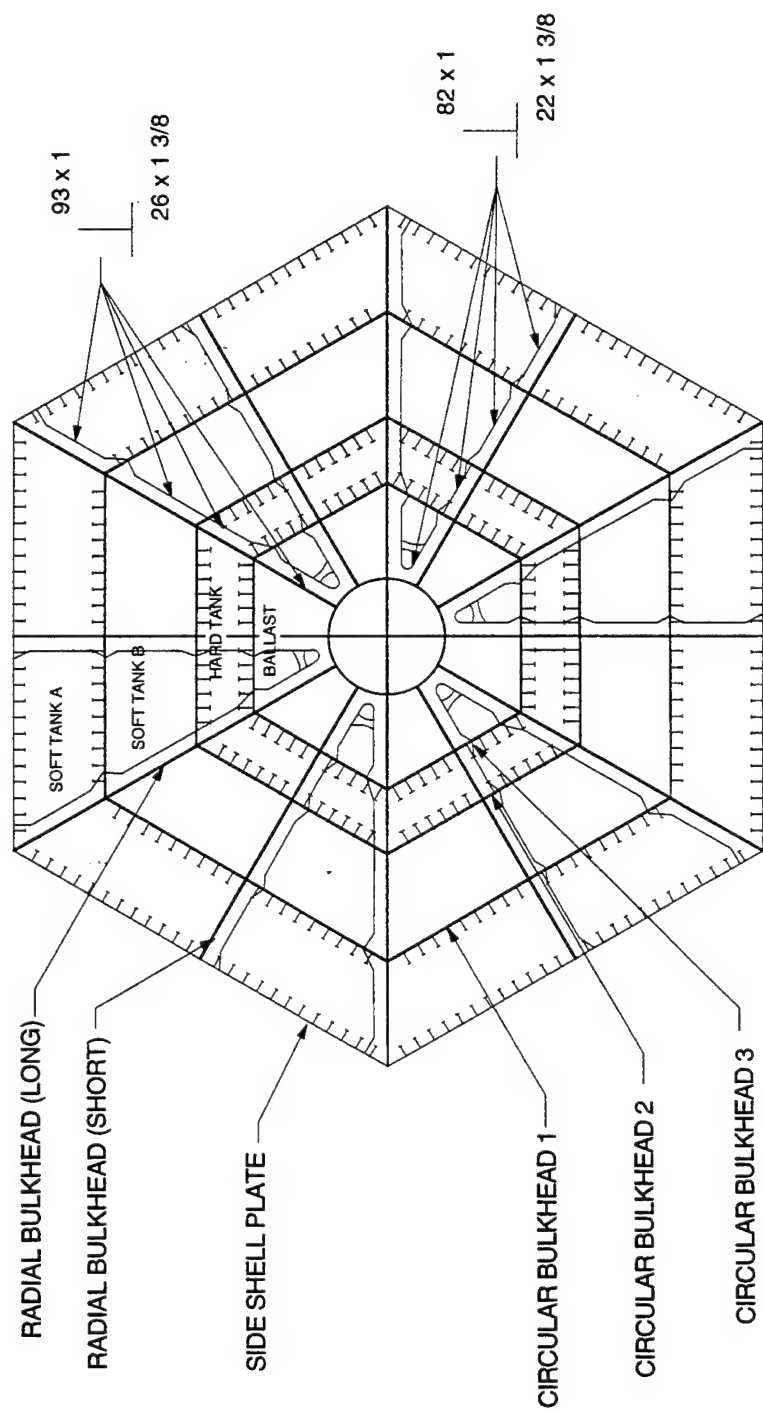


Figure 3.4 The ASOP hull cross section framing

| | STIFFENER | GIRDER | PLATE THICKNESS |
|--------------|------------|---------------|-----------------|
| SOFT TANK 1 | L8x6x1 1/8 | 93x1x26x1 3/8 | 3/4" |
| SOFT TANK 2 | L8x6x1 1/8 | 93x1x26x1 3/8 | 3/4" |
| HARD TANK | 16x1x8x1 | 93x1x26x1 3/8 | 1" |
| BALLAST TANK | 16x1x8x1 | 93x1x26x1 3/8 | 1" |

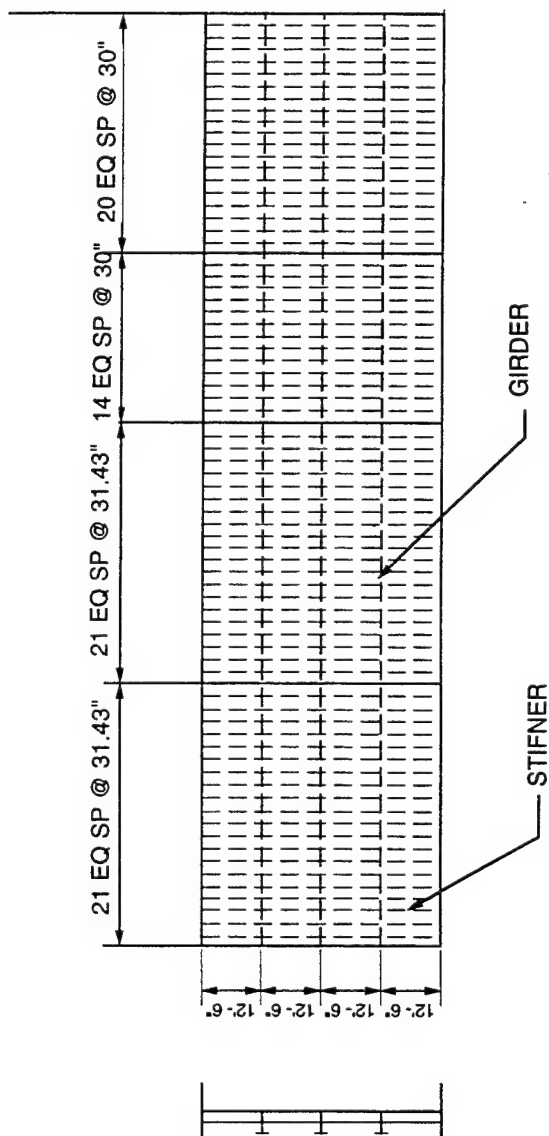


Figure 3.5 The radial bulkhead (long) framing

| | STIFFENER | GIRDER | PLATE THICKNESS |
|--------------|------------|---------------|-----------------|
| SOFT TANK 1 | L8x6x1 1/8 | 82x1x22x1 3/8 | 3/4" |
| SOFT TANK 2 | L8x6x1 1/8 | 82x1x22x1 3/8 | 3/4" |
| HARD TANK | 16x1x8x1 | 82x1x22x1 3/8 | 1" |
| BALLAST TANK | 16x1x8x1 | 82x1x22x1 3/8 | 1" |

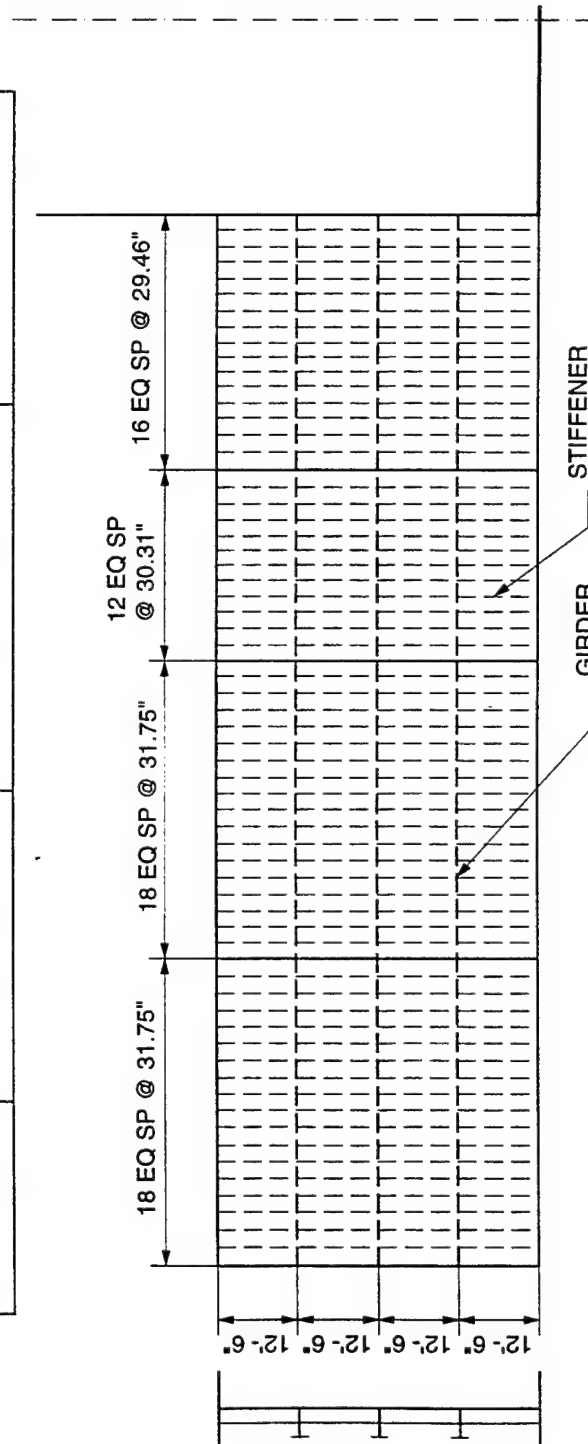


Figure 3.6 The radial bulkhead (short) framing

| | STIFFENER | GIRDER | PLATE THICKNESS |
|---------------------|-----------|-----------------|-----------------|
| SIDE SHELL | L8x4x3/4 | 70x3/4x20x1 1/4 | 3/4" |
| CIRCULAR BULKHEAD 1 | L8x4x3/4 | 70x3/4x20x1 1/4 | 3/4" |
| CIRCULAR BULKHEAD 2 | L9x6x11/8 | 93x1x26x1 1/4 | 1" |
| CIRCULAR BULKHEAD 3 | L9x6x11/8 | 93x1x26x1 1/4 | 1" |

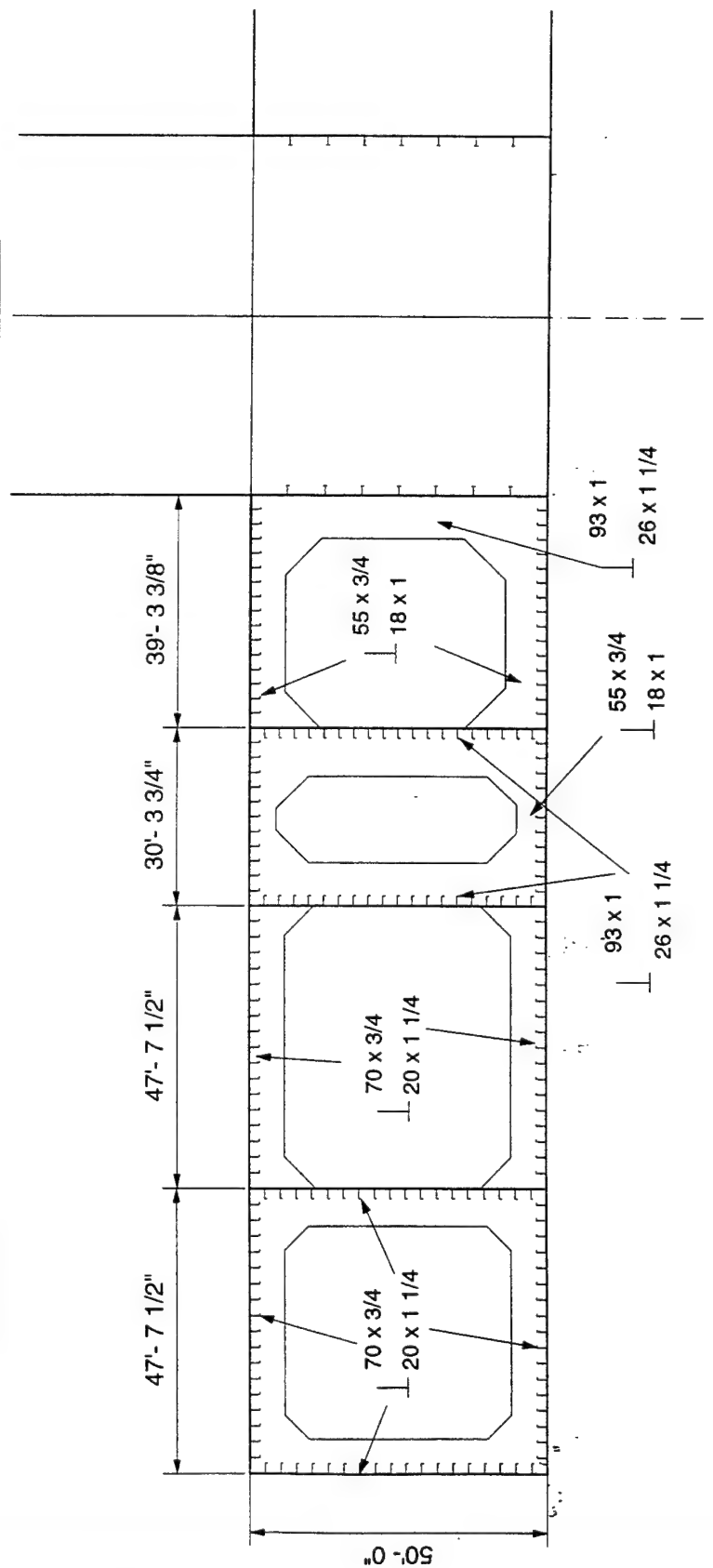
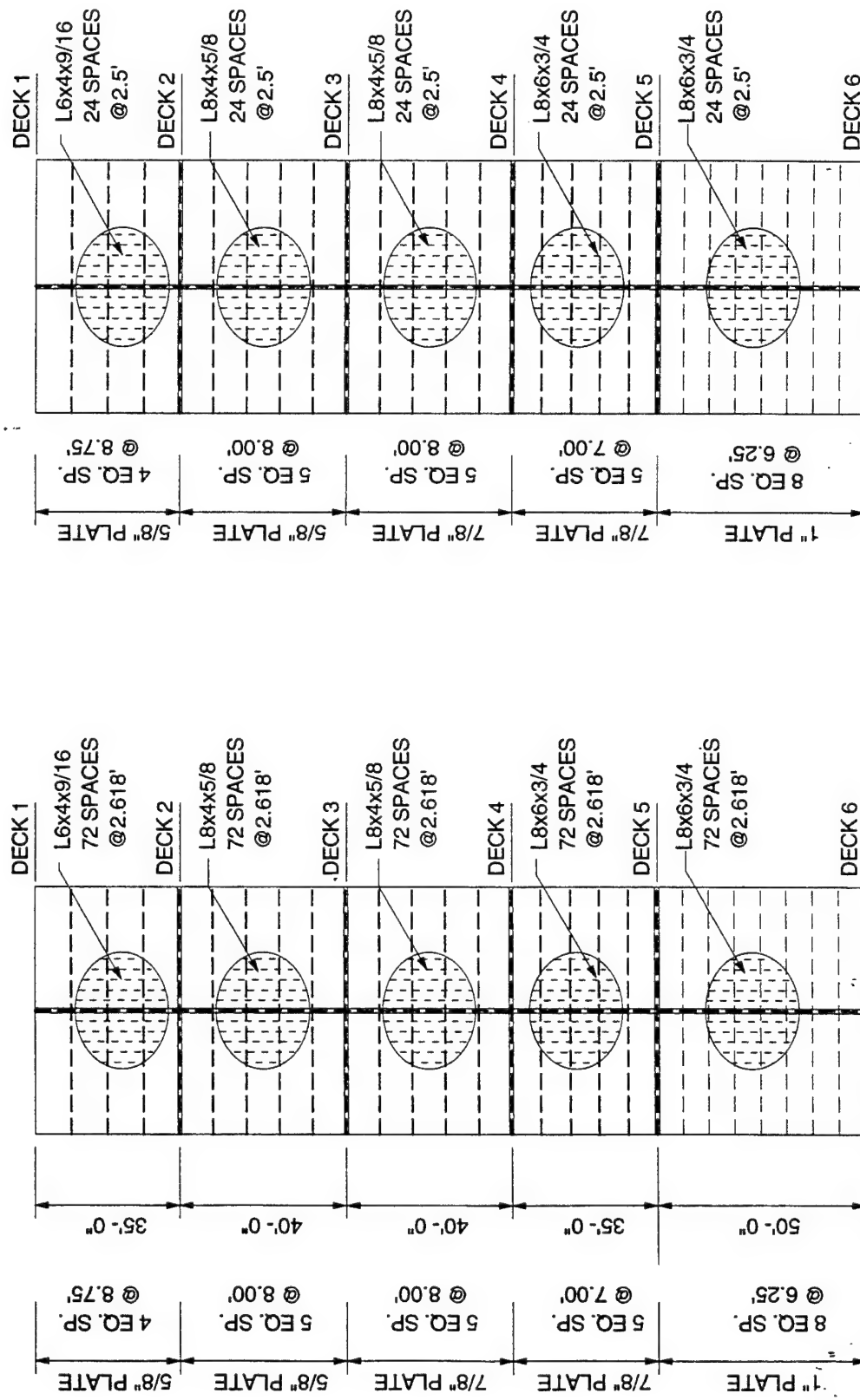


Figure 3.7 The circular bulkheads framing



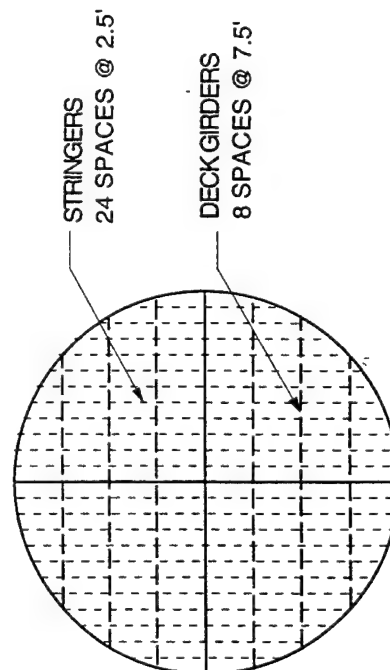
CENTRAL COLUMN BULKHEAD FRAMING

CENTRAL COLUMN OUTER SHELL FRAME

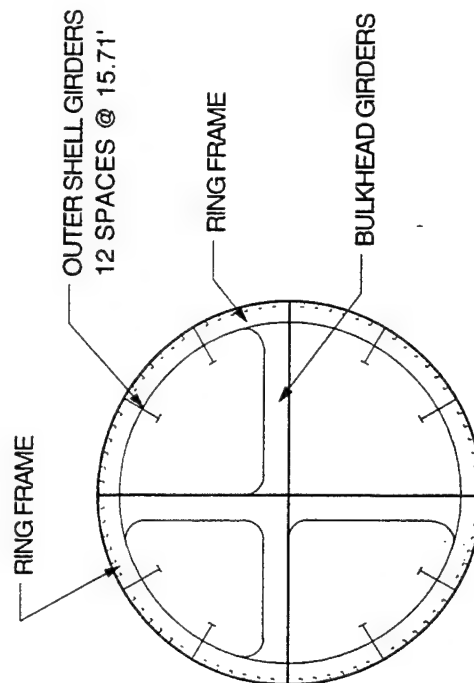
Figure 3.8 The center column outer shell and bulkhead framing

| DECK | DECK PLATE | DECK STRINGERS | DECK GIRDER |
|------|------------|----------------|-----------------|
| 1 | 1/2" | L6x4x9/16 | 45x1/2x10x1 |
| 2 | 1/2" | L6x4x9/16 | 45x1/2x10x1 |
| 3 | 9/16" | L6x4x9/16 | 45x1/2x10x1 |
| 4 | 9/16" | L8X4X5/8 | 50x5/8x14x1 |
| 5 | 9/16" | L8X6X3/4 | 65x5/8x16x1 |
| 6 | 9/16" | L8X8X7/8 | 75x5/8x18x1 1/8 |

| BETWEEN DECK | OUTERSHELL GIRDER | RING FRAME | B/H GIRDER |
|--------------|-------------------|-------------|-----------------|
| 1 & 2 | 56x1/2x10x3/4 | 25x1/2x10x1 | 45x1/2x10x1 |
| 2 & 4 | 75x5/8x15x1 | 25x1/2x10x1 | 45x1/2x10x1 |
| 3 & 4 | 75x5/8x15x1 | 25x1/2x10x1 | 50x5/8x14x1 |
| 4 & 5 | 85x5/8x20x1 | 35x1/2x12x1 | 65x5/8x16x1 |
| 5 & 6 | - | 35x1/2x12x1 | 75x5/8x18x1 1/8 |



DECK FRAMING



SECTION-BETWEEN 1&2

Figure 3.9 The center column deck and section framing

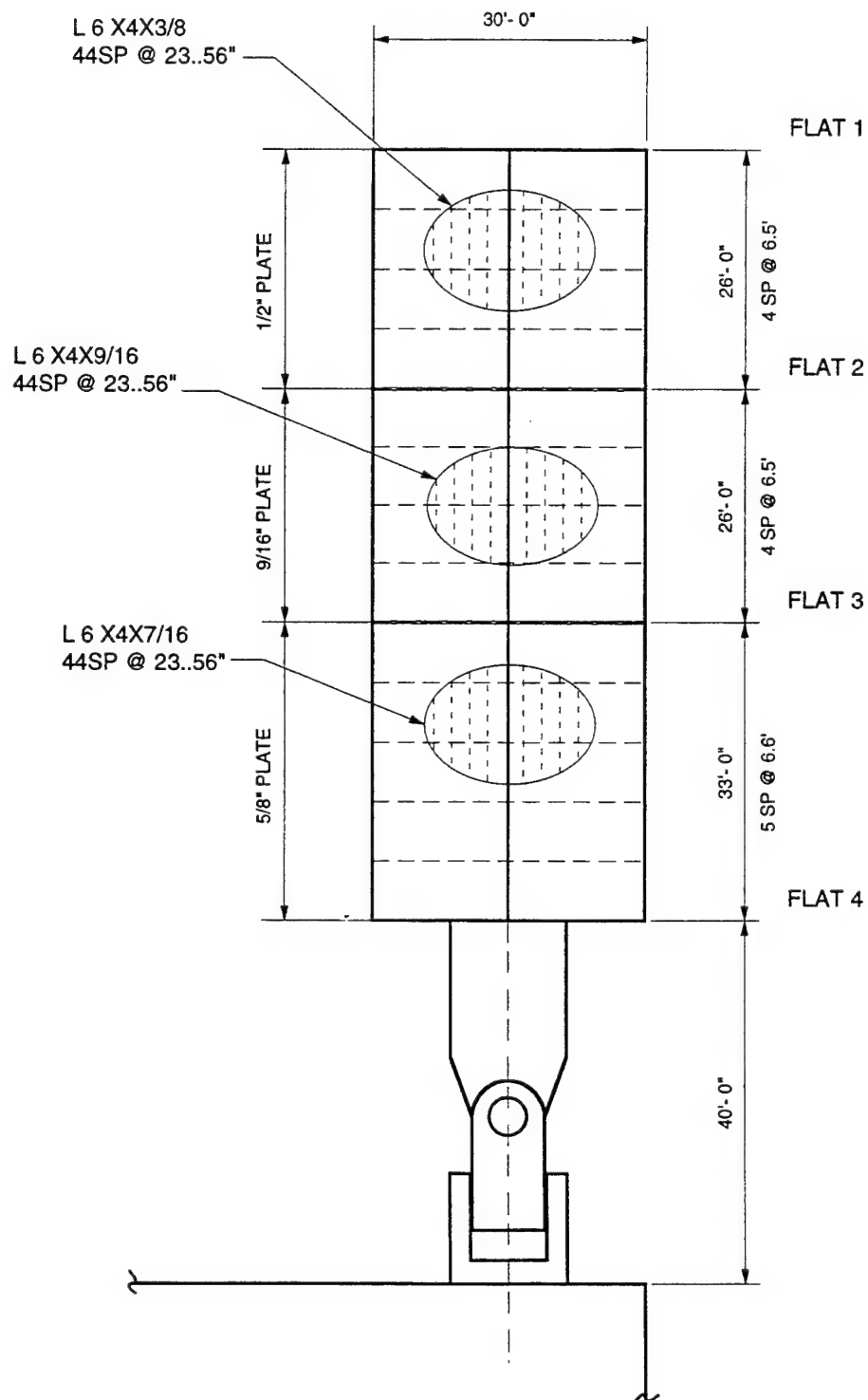


Figure 3.10 The buoy outer shell framing

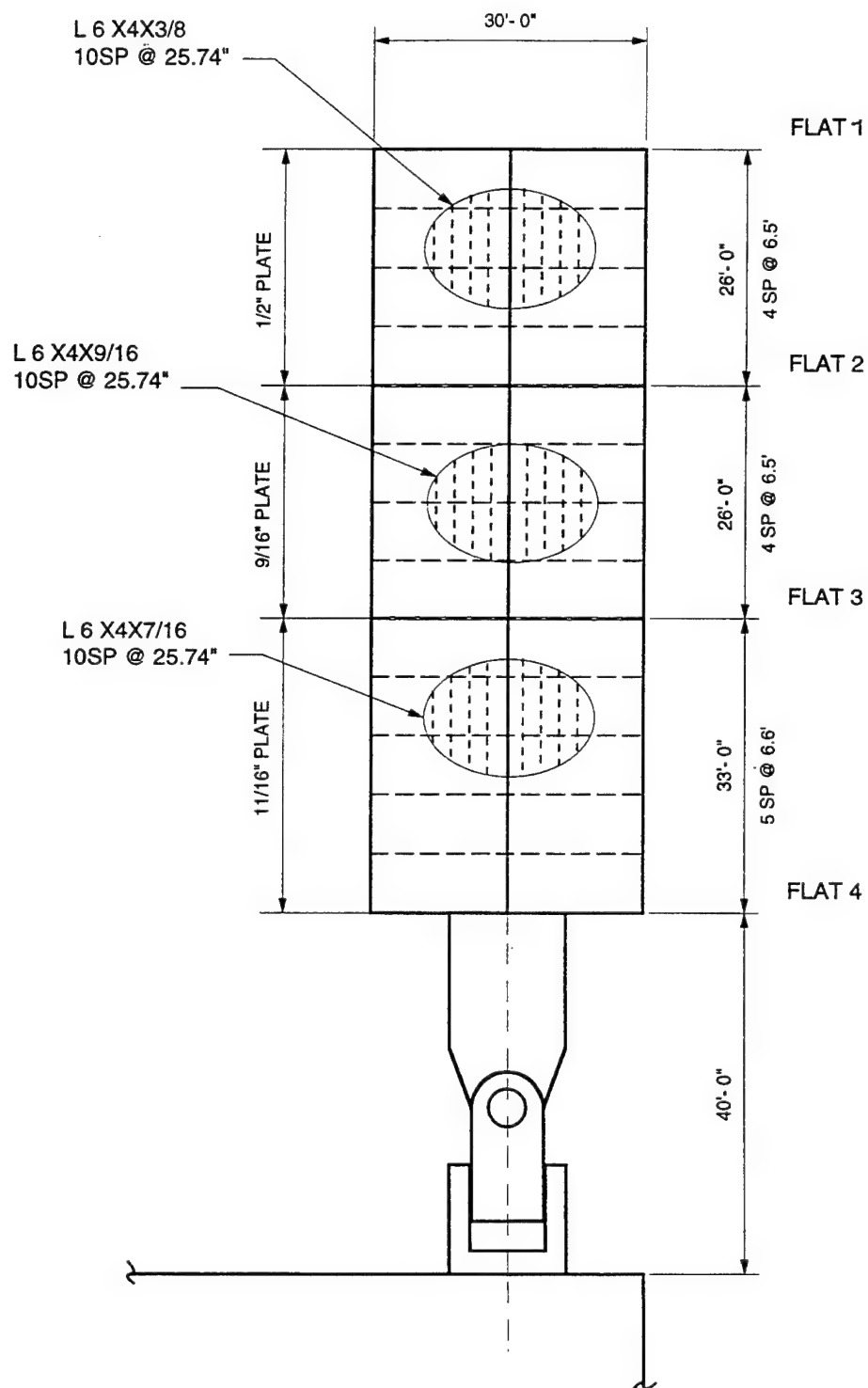
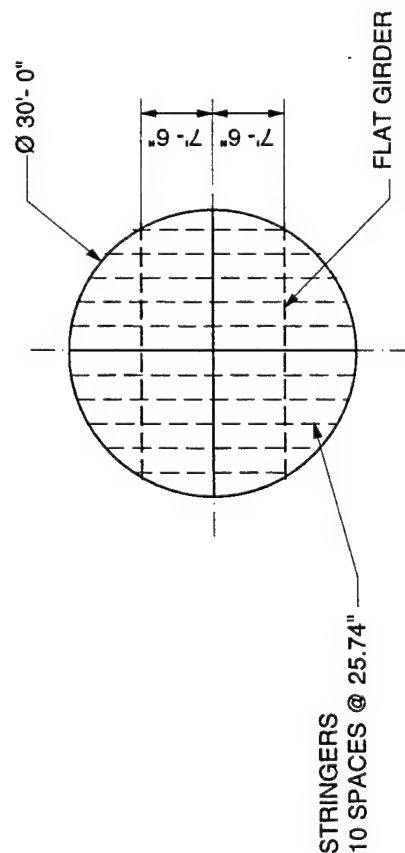


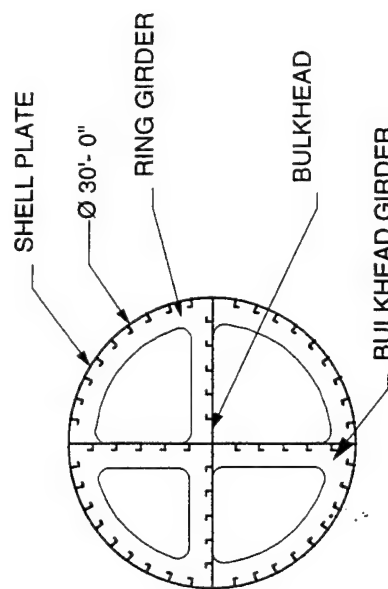
Figure 3.11 The buoy bulkhead framing

| FLAT | FLAT PLATE | FLAT STRINGERS | FLAT GIRDER |
|------|------------|----------------|----------------|
| 1 | 1/2" | L6x4x3/8 | 23x7/16x10x1/2 |
| 2 | 1/2" | L6x4x3/8 | 23x7/16x10x1/2 |
| 3 | 9/16" | L8x4x7/16 | 23x7/16x10x3/4 |
| 4 | 9/16" | L8X6X9/16 | 25x1/2x12x1 |

| BETWEEN FLAT | RING GIRDER | B/H GIRDER |
|-----------------|----------------|----------------|
| 1 & 2 | 36x7/16x10x1/2 | 23x7/16x10x1/2 |
| 2 & 4 | 36x1/2x12x1 | 23x7/16x10x3/4 |
| 3 & 4 | 40x1/2x17x1 | 25x1/2x12x1 |



FLAT FRAMING



SECTION - BETWEEN FLAT 1 & 2

Figure 3.12 The buoy flat and section framing

Table 3.1 The buoy outer shell and bulkhead plating

| PLATE LOCATION | STIFFENER SPACING (IN) | FRAME SPACING (FT) | HEAD (FT) | ABS THICKNESS (IN) | ACTUAL THICKNESS (IN) |
|-----------------------|------------------------|--------------------|-----------|--------------------|-----------------------|
| OUTER SHELL PL | | | | | |
| COMPARTMENT 1 | 23.56 | 6.5380 | 30.00 | 0.381 | 0.5000 O.K. |
| COMPARTMENT 2 | 23.56 | 6.5380 | 63.00 | 0.507 | 0.5625 O.K. |
| COMPARTMENT 3 | 23.56 | 6.5380 | 95.00 | 0.599 | 0.6250 O.K. |
| BULKHEAD | | | | | |
| COMPARTMENT 1 | 25.74 | 6.5380 | 30.00 | 0.406 | 0.5000 O.K. |
| COMPARTMENT 2 | 25.74 | 6.5380 | 63.00 | 0.544 | 0.5625 O.K. |
| COMPARTMENT 3 | 25.74 | 6.5380 | 95.00 | 0.645 | 0.6875 O.K. |
| HORI. FLAT | | | | | |
| FLAT 1 | 25.74 | 7.5000 | 30.00 | 0.406 | 0.5000 O.K. |
| FLAT 2 | 25.74 | 7.5000 | 30.00 | 0.406 | 0.5000 O.K. |
| FLAT 3 | 25.74 | 7.5000 | 63.00 | 0.544 | 0.5625 O.K. |
| FLAT 4 | 25.74 | 7.5000 | 95.00 | 0.645 | 0.6875 O.K. |

Table 3.2 The buoy frame structural (girder) scantling

| LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|---------------|------|-----------|-----------|-----------|-------|------------------|--------------|----------------------|-----------|
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| OUT SHELL | | | | | | | | | |
| | | | | | | | | | |
| COMPARTMENT 1 | 1.50 | 24.00 | 6.538 | 23.562 | 0.720 | 235.20 | 343.31 | 36 X 7/16 X 10 X 1/2 | O.K. |
| COMPARTMENT 2 | 1.50 | 57.00 | 6.538 | 23.562 | 0.720 | 558.61 | 582.33 | 36 X 1/2 X 12 X 1 | O.K. |
| COMPARTMENT 3 | 1.50 | 89.00 | 6.538 | 23.562 | 0.720 | 872.21 | 882.42 | 40 X 3/4 X 17 X 1 | O.K. |
| | | | | | | | | | |
| BULKHEAD | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| COMPARTMENT 1 | 1.50 | 24.00 | 6.538 | 15.000 | 0.720 | 95.32 | 179.98 | 23 X 7/16 X 10 X 1/2 | O.K. |
| COMPARTMENT 2 | 1.50 | 57.00 | 6.538 | 15.000 | 0.720 | 226.39 | 235.31 | 23 X 7/16 X 10 X 3/4 | O.K. |
| COMPARTMENT 3 | 1.50 | 89.00 | 6.538 | 15.000 | 0.720 | 353.49 | 380.59 | 25 X 1/2 X 12 X 1 | O.K. |
| | | | | | | | | | |
| HORI. FLAT | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| FLAT 1 | 1.50 | 30.00 | 7.500 | 12.990 | 0.720 | 102.51 | 179.98 | 23 X 7/16 X 10 X 1/2 | O.K. |
| FLAT 2 | 1.50 | 30.00 | 7.500 | 12.990 | 0.720 | 102.51 | 179.98 | 23 X 7/16 X 10 X 1/2 | O.K. |
| FLAT 3 | 1.50 | 63.00 | 7.500 | 12.990 | 0.720 | 215.27 | 235.31 | 23 X 7/16 X 10 X 3/4 | O.K. |
| FLAT 4 | 1.50 | 95.00 | 7.500 | 12.990 | 0.720 | 324.61 | 380.59 | 25 X 1/2 X 12 X 1 | O.K. |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

Table 3.3 The buoy frame structural (stiffener) scantling

| STIFF LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|----------------|------|--------|--------|--------|-------|---------------|-----------|---------------|-----------|
| OUTER SHELL | | | | | | | | | |
| COMPARTMENT 1 | 1.00 | 27.00 | 1.963 | 6.538 | 0.720 | 6.69 | 12.41 | L6 X4 X 3/8 | O.K. |
| COMPARTMENT 2 | 1.00 | 60.00 | 1.963 | 6.538 | 0.720 | 14.86 | 17.63 | L6 x 4 x 9/16 | O.K. |
| COMPARTMENT 3 | 1.00 | 92.00 | 1.963 | 6.538 | 0.720 | 22.79 | 28.31 | L8 x 4 x 7/16 | O.K. |
| BULKHEAD | | | | | | | | | |
| COMPARTMENT 1 | 1.00 | 27.00 | 2.145 | 6.538 | 0.720 | 7.31 | 12.41 | L6 X4 X 3/8 | O.K. |
| COMPARTMENT 2 | 1.00 | 60.00 | 2.145 | 6.538 | 0.720 | 16.24 | 17.63 | L6 x 4 x 9/16 | O.K. |
| COMPARTMENT 3 | 1.00 | 92.00 | 2.145 | 6.538 | 0.720 | 24.90 | 28.31 | L8 x 4 x 7/16 | O.K. |
| HORI. FLAT | | | | | | | | | |
| FLAT1 | 1.00 | 30.00 | 2.145 | 7.500 | 0.720 | 10.69 | 12.41 | L6 X4 X 3/8 | O.K. |
| FLAT2 | 1.00 | 30.00 | 2.145 | 7.500 | 0.720 | 10.69 | 12.41 | L6 X4 X 3/8 | O.K. |
| FLAT3 | 1.00 | 63.00 | 2.145 | 7.500 | 0.720 | 22.44 | 28.31 | L8 x 4 x 7/16 | O.K. |
| FLAT4 | 1.00 | 95.00 | 2.145 | 7.500 | 0.720 | 33.84 | 34.29 | L8 x 6 x 9/16 | O.K. |

Table 3.4 The hull outer shell and bulkhead plating

| PLATE LOCATION | STIFFENER SPACING (IN) | FRAME SPACING (FT) | HEAD (FT) | ABS THICKNESS (IN) | ACTUAL THICKNESS (IN) |
|---------------------|------------------------|--------------------|-----------|--------------------|-----------------------|
| SOFT TANK | | | | | |
| SIDE HELL | 31.75 | 8.5000 | 53.00 | 0.602 | 0.750 O.K. |
| TOP PLATE | 31.75 | 8.5000 | 53.00 | 0.603 | 0.750 O.K. |
| BOTTOM PLATE | 31.75 | 8.5000 | 53.00 | 0.602 | 0.750 O.K. |
| RADIAL BULKHEAD | 31.75 | 12.5000 | 53.00 | 0.602 | 0.750 O.K. |
| HARD TANK | | | | | |
| SIDE HELL | 30.31 | 7.5000 | 165.00 | 0.946 | 1.000 O.K. |
| TOP PLATE | 30.31 | 7.5000 | 115.00 | 0.807 | 1.000 O.K. |
| BOTTOM PLATE | 30.31 | 7.5000 | 165.00 | 0.946 | 1.000 O.K. |
| RADIAL BULKHEAD | 30.31 | 12.5000 | 165.00 | 0.946 | 1.000 O.K. |
| BALLAST TANK | | | | | |
| SIDE HELL | 30.00 | 7.5000 | 165.00 | 0.938 | 1.000 O.K. |
| TOP PLATE | 30.00 | 7.5000 | 115.00 | 0.799 | 1.000 O.K. |
| BOTTOM PLATE | 30.00 | 7.5000 | 165.00 | 0.938 | 1.000 O.K. |
| RADIAL BULKHEAD | 30.00 | 12.5000 | 165.00 | 0.938 | 1.000 O.K. |

Table 3.5 The hull Frame structural (girder) scantling

| LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|-------------------|------|-----------|-----------|-----------|-------|------------------|--------------|-------------------------|-------------------|
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| SOFT TANK 1 | | | | | | | | | |
| SIDE | 1.50 | 53.00 | 8.50 | 38.330 | 0.720 | 1787.05 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| TOP | 1.50 | 53.00 | 8.50 | 37.000 | 0.720 | 1665.18 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| BOTTOM | 1.50 | 53.00 | 8.50 | 37.000 | 0.720 | 1665.18 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| | | | | | | | | | |
| SOFT TANK 2 | | | | | | | | | |
| TOP | 1.50 | 53.00 | 8.50 | 45.630 | 0.720 | 2532.56 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| BOTTOM | 1.50 | 53.00 | 8.50 | 45.630 | 0.720 | 2532.56 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| | | | | | | | | | |
| HARD TANK | | | | | | | | | |
| SIDE | 1.50 | 165.00 | 7.50 | 39.580 | 0.720 | 5234.32 | 5309.08 | 93 X 1 X 26 X 1 3/8 | O.K. |
| TOP | 1.50 | 115.00 | 7.50 | 15.000 | 0.720 | 523.97 | 1615.14 | 55 X 3/4 X 18 X 1 | O.K. |
| BOTTOM | 1.50 | 165.00 | 7.50 | 15.000 | 0.720 | 751.78 | 1615.14 | 55 X 3/4 X 18 X 1 | O.K. |
| | | | | | | | | | |
| BALLAST TANK | | | | | | | | | |
| SIDE | 1.50 | 165.00 | 7.50 | 37.330 | 0.720 | 4656.13 | 5309.08 | 93 X 1 1/8 X 26 X 1 3/8 | O.K. |
| TOP | 1.50 | 115.00 | 7.50 | 33.550 | 0.720 | 2621.25 | 2654.00 | 70 X 1 X 20 X 1 1/4 | O.K. |
| BOTTOM | 1.50 | 165.00 | 7.50 | 33.550 | 0.720 | 3760.92 | 4088.66 | 82 X 1 X 22 X 1 3/8 | O.K. |
| | | | | | | | | | |
| RADIAL BULKHEAD 1 | | | | | | | | | |
| SOFT TANK | 1.50 | 53.00 | 12.50 | 44.630 | 0.720 | 3562.90 | 4088.66 | 82 X 1 X 22 X 1 3/8 | O.K. |
| HARD TANK | 1.50 | 152.50 | 12.50 | 27.300 | 0.720 | 3835.91 | 4088.66 | 82 X 1 X 22 X 1 3/8 | O.K. |
| BALLAST TANK | 1.50 | 152.50 | 12.50 | 36.800 | 0.720 | 6970.10 | 4088.66 | 82 X 1 X 22 X 1 3/8 | O.K. (WITH STRUT) |
| | | | | | | | | | |
| RADIAL BULKHEAD 2 | | | | | | | | | |
| SOFT TANK | 1.50 | 53.00 | 12.50 | 52.000 | 0.720 | 4836.78 | 5309.08 | 93 X 1 1/8 X 26 X 1 3/8 | O.K. |
| HARD TANK | 1.50 | 152.50 | 12.50 | 32.000 | 0.720 | 5270.40 | 5309.08 | 93 X 1 1/8 X 26 X 1 3/8 | O.K. |
| BALLAST TANK | 1.50 | 152.50 | 12.50 | 42.500 | 0.720 | 9296.54 | 5309.08 | 93 X 1 1/8 X 26 X 1 3/8 | O.K. (WITH STRUT) |

Table 3.6 The hull Frame structural (stiffener) scantling

| STIFF LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|--------------------------------------|------|--------|--------|--------|-------|---------------|-----------|----------------|-----------|
| SHELL & CIRCULAR BULKHEAD | | | | | | | | | |
| SOFT TANK | 1.00 | 52.00 | 2.646 | 8.500 | 0.720 | 29.35 | 34.38 | L8 X4 X 3/4 | O.K. |
| HARD TANK | 1.00 | 165.00 | 2.526 | 7.500 | 0.720 | 69.21 | 75.90 | L9 x 6 x 1 1/8 | O.K. |
| BALLAST TANK | 1.00 | 165.00 | 2.500 | 7.500 | 0.720 | 68.50 | 75.90 | L9 x 6 x 1 1/8 | O.K. |
| RADIAL BULKHEAD | | | | | | | | | |
| SOFT TANK | 1.00 | 52.00 | 2.646 | 12.500 | 0.720 | 63.46 | 63.55 | L8 x 6 x 1 1/8 | O.K. |
| HARD TANK | 1.00 | 165.00 | 2.526 | 12.500 | 0.720 | 192.24 | 195.97 | 16 X 1 X 8 X 1 | O.K. |
| BALLAST TANK | 1.00 | 165.00 | 2.500 | 12.500 | 0.720 | 190.27 | 195.97 | 16 X 1 X 8 X 1 | O.K. |
| TOP PLATE | | | | | | | | | |
| SOFT TANK | 1.00 | 53.00 | 2.646 | 8.500 | 0.720 | 29.91 | 34.38 | L8 X4 X 3/4 | O.K. |
| HARD TANK | 1.00 | 115.00 | 2.526 | 7.500 | 0.720 | 48.24 | 58.41 | L8 X6 X 1 | O.K. |
| BALLAST TANK | 1.00 | 115.00 | 2.500 | 7.500 | 0.720 | 47.74 | 58.41 | L8 X6 X 1 | O.K. |
| BOTTOM PLATE | | | | | | | | | |
| SOFT TANK | 1.00 | 53.00 | 2.646 | 8.500 | 0.720 | 29.91 | 34.38 | L8 X4 X 3/4 | O.K. |
| HARD TANK | 1.00 | 165.00 | 2.526 | 7.500 | 0.720 | 69.21 | 75.90 | L9 x 6 x 1 1/8 | O.K. |
| BALLAST TANK | 1.00 | 165.00 | 2.500 | 7.500 | 0.720 | 68.50 | 75.90 | L9 x 6 x 1 1/8 | O.K. |

Table 3.7 The center column outer shell and bulkhead plating

| PLATE LOCATION | STIFFENER SPACING (IN) | FRAME SPACING (FT) | HEAD (FT) | ABS THICKNESS (IN) | ACTUAL THICKNESS (IN) |
|-----------------------|------------------------|--------------------|-----------|--------------------|-----------------------|
| OUTER SHELL PL | | | | | |
| COMPARTMENT 1 | 31.415 | 8.7500 | 35.00 | 0.504 | 0.625 O.K. |
| COMPARTMENT 2 | 31.415 | 8.0000 | 40.00 | 0.532 | 0.625 O.K. |
| COMPARTMENT 3 | 31.415 | 8.0000 | 80.00 | 0.711 | 0.875 O.K. |
| COMPARTMENT 4 | 31.415 | 7.0000 | 115.00 | 0.832 | 0.875 O.K. |
| COMPARTMENT 5 | 31.415 | 6.2500 | 165.00 | 0.977 | 1.000 O.K. |
| BULKHEAD | | | | | |
| COMPARTMENT 1 | 30.000 | 8.7500 | 35.00 | 0.486 | 0.625 O.K. |
| COMPARTMENT 2 | 30.000 | 8.0000 | 40.00 | 0.512 | 0.625 O.K. |
| COMPARTMENT 3 | 30.000 | 8.0000 | 80.00 | 0.683 | 0.875 O.K. |
| COMPARTMENT 4 | 30.000 | 7.5000 | 115.00 | 0.799 | 0.875 O.K. |
| COMPARTMENT 5 | 30.000 | 6.2500 | 165.00 | 0.938 | 1.000 O.K. |
| DECK | | | | | |
| DECK1 | 30.000 | 7.5000 | 35.00 | 0.486 | 0.500 O.K. |
| DECK2 | 30.000 | 7.5000 | 35.00 | 0.486 | 0.500 O.K. |
| DECK3 | 30.000 | 7.5000 | 40.00 | 0.512 | 0.625 O.K. |
| DECK4 | 30.000 | 7.5000 | 80.00 | 0.683 | 0.875 O.K. |
| DECK5 | 30.000 | 7.5000 | 115.00 | 0.799 | 0.875 O.K. |
| DECK6 | 30.000 | 7.5000 | 165.00 | 0.938 | 1.000 O.K. |

Table 3.8 The center column frame structural (girder) scantling

| LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|---------------|------|-----------|-----------|-----------|-------|------------------|--------------|-------------------------|-----------|
| OUT SHELL | | | | | | | | | |
| LONG GIRDER | | | | | | | | | |
| COMPARTMENT 1 | 1.50 | 20.00 | 15.710 | 32.000 | 0.720 | 868.70 | 1109.60 | 65 X 7/8 X 10 X 3/4 | O.K. |
| COMPARTMENT 2 | 1.50 | 40.00 | 15.710 | 37.000 | 0.720 | 2322.75 | 2605.52 | 75 X 1 X 15 X 1 | O.K. |
| COMPARTMENT 3 | 1.50 | 65.00 | 15.710 | 37.000 | 0.720 | 3774.48 | 3852.61 | 85 X 1 X 20 X 1 1/8 | O.K. |
| COMPARTMENT 4 | 1.50 | 100.00 | 15.710 | 32.000 | 0.720 | 4343.50 | 4529.69 | 90 X 1 1/8 X 22 X 1 1/4 | O.K. |
| RING FRAME | | | | | | | | | |
| COMPARTMENT 1 | 1.50 | 27.00 | 8.750 | 15.710 | 0.720 | 157.43 | 334.46 | 25 X 1/2 X 10 X 1 | O.K. |
| COMPARTMENT 2 | 1.50 | 32.00 | 8.000 | 15.710 | 0.720 | 170.59 | 334.46 | 25 X 1/2 X 10 X 1 | O.K. |
| COMPARTMENT 3 | 1.50 | 72.00 | 8.000 | 15.710 | 0.720 | 383.83 | 334.46 | 25 X 1/2 X 10 X 1 | O.K. |
| COMPARTMENT 4 | 1.50 | 108.00 | 7.000 | 15.710 | 0.720 | 503.78 | 591.92 | 35 X 1/2 X 12 X 1 | O.K. |
| COMPARTMENT 5 | 1.50 | 158.75 | 6.250 | 15.710 | 0.720 | 661.17 | 731.31 | 45 X 1/2 X 10 X 1 | O.K. |
| BULKHEAD | | | | | | | | | |
| COMPARTMENT 1 | 1.50 | 27.00 | 8.750 | 30.000 | 0.720 | 574.09 | 731.31 | 45 X 1/2 X 10 X 1 | O.K. |
| COMPARTMENT 2 | 1.50 | 32.00 | 8.000 | 30.000 | 0.720 | 622.08 | 731.31 | 45 X 1/2 X 10 X 1 | O.K. |
| COMPARTMENT 3 | 1.50 | 72.00 | 8.000 | 30.000 | 0.720 | 1399.68 | 1702.52 | 65 X 7/8 X 16 X 1 | O.K. |
| COMPARTMENT 4 | 1.50 | 108.00 | 7.000 | 30.000 | 0.720 | 1837.08 | 2433.41 | 75 X 1 X 18 X 1 1/8 | O.K. |
| COMPARTMENT 5 | 1.50 | 158.75 | 6.250 | 30.000 | 0.720 | 2411.02 | 2433.41 | 75 X 1 X 18 X 1 1/8 | O.K. |
| DECK | | | | | | | | | |
| DECK1 | 1.50 | 35.00 | 7.500 | 29.000 | 0.720 | 596.06 | 731.31 | 45 X 1/2 X 10 X 1 | O.K. |
| DECK2 | 1.50 | 35.00 | 7.500 | 29.000 | 0.720 | 596.06 | 731.31 | 45 X 1/2 X 10 X 1 | O.K. |
| DECK3 | 1.50 | 45.00 | 7.500 | 29.000 | 0.720 | 766.36 | 1702.52 | 65 X 7/8 X 16 X 1 | O.K. |
| DECK4 | 1.50 | 85.00 | 7.500 | 29.000 | 0.720 | 1447.57 | 1702.52 | 65 X 7/8 X 16 X 1 | O.K. |
| DECK5 | 1.50 | 115.00 | 7.500 | 29.000 | 0.720 | 1958.48 | 2433.41 | 75 X 1 X 18 X 1 1/8 | O.K. |
| DECK6 | 1.50 | 165.00 | 7.500 | 29.000 | 0.720 | 2809.99 | 3074.34 | 85 X 1 X 20 X 1 | O.K. |

Table 3.9 The center column frame structural (stiffener) scantling

| STIFF LOCATION | C | H (FT) | S (FT) | L (FT) | Q | ABS REQ'D. SM | ACTUAL SM | ACTUAL SIZE | RECOMMEND |
|--------------------|------|-----------|-----------|-----------|-------|------------------|--------------|--------------|-----------|
| OUTER SHELL | | | | | | | | | |
| COMPARTMENT 1 | 1.00 | 35.00 | 2.618 | 8.750 | 0.720 | 20.71 | 29.04 | L8 x 4 x 5/8 | O.K. |
| COMPARTMENT 2 | 1.00 | 45.00 | 2.618 | 8.000 | 0.720 | 22.26 | 46.09 | L8 x 6 x 3/4 | O.K. |
| COMPARTMENT 3 | 1.00 | 85.00 | 2.618 | 8.000 | 0.720 | 42.04 | 46.09 | L8 x 6 x 3/4 | O.K. |
| COMPARTMENT 4 | 1.00 | 115.00 | 2.618 | 7.000 | 0.720 | 43.55 | 53.49 | L9 x 6 x 3/4 | O.K. |
| COMPARTMENT 5 | 1.00 | 165.00 | 2.618 | 6.250 | 0.720 | 49.81 | 53.13 | L9 x 6 x 3/4 | O.K. |
| BULKHEAD | | | | | | | | | |
| COMPARTMENT 1 | 1.00 | 35.00 | 2.500 | 8.750 | 0.720 | 19.78 | 29.04 | L8 x 4 x 5/8 | O.K. |
| COMPARTMENT 2 | 1.00 | 45.00 | 2.500 | 8.000 | 0.720 | 21.25 | 46.09 | L8 x 6 x 3/4 | O.K. |
| COMPARTMENT 3 | 1.00 | 85.00 | 2.500 | 8.000 | 0.720 | 40.15 | 46.09 | L8 x 6 x 3/4 | O.K. |
| COMPARTMENT 4 | 1.00 | 115.00 | 2.500 | 7.000 | 0.720 | 41.59 | 53.49 | L9 x 6 x 3/4 | O.K. |
| COMPARTMENT 5 | 1.00 | 165.00 | 2.500 | 6.250 | 0.720 | 47.57 | 53.13 | L9 x 6 x 3/4 | O.K. |
| DECK | | | | | | | | | |
| DECK1 | 1.00 | 35.00 | 2.500 | 7.500 | 0.720 | 14.53 | 17.99 | L6 X4 X 9/16 | O.K. |
| DECK2 | 1.00 | 35.00 | 2.500 | 7.500 | 0.720 | 14.53 | 17.99 | L6 X4 X 9/16 | O.K. |
| DECK3 | 1.00 | 45.00 | 2.500 | 7.500 | 0.720 | 18.68 | 29.04 | L8 x 4 x 5/8 | O.K. |
| DECK4 | 1.00 | 85.00 | 2.500 | 7.500 | 0.720 | 35.29 | 45.98 | L8 x 6 x 3/4 | O.K. |
| DECK5 | 1.00 | 115.00 | 2.500 | 7.500 | 0.720 | 47.74 | 53.69 | L9 x 6 x 3/4 | O.K. |
| DECK6 | 1.00 | 165.00 | 2.500 | 7.500 | 0.720 | 68.50 | 71.80 | L9 x 8 x 7/8 | O.K. |

Table 3.10 Structural and fixed equipment weight

| <u>Item</u> | <u>Weight (kips)</u> |
|-------------------------------|----------------------|
| Topside | |
| Total weight | 12,000 |
| Hull | |
| Structural steel | 72,711 |
| Fixed ballast | 4,204 |
| Piping system | 1,000 |
| Mooring winches and equipment | 800 |
| Universal joints (6) | 900 |
| Hull fittings and anodes | 1,000 |
| Ladders | 500 |
| Total weight | 81,115 |
| Buoys (6) | |
| Structural steel | 4,620 |
| Outfitting | 480 |
| Total weight | 5,100 |
| Total weight without buoys | 93,115 |
| Total weight with buoys | 98,215 |

Table 3.11 Weight list at operational draft (145 ft)

ASOP without buoys

| | |
|---|--------------------|
| Structural and fixed weight (without buoys) | 93,115 kips |
| Fuel Storage | 306,300 kips |
| Variable payload | 3,000 kips |
| Water ballast | 44,000 kips |
| Total weight | 446,415 kips |
| C.G. | 33 ft (above keel) |
| Radius of gyration | |
| Roll | 109 ft |
| Pitch | 109 ft |
| Yaw | 142 ft |

Buoy

| | |
|--------------------|----------------------------|
| Total weight | 850 kips each |
| C.G. | 43 ft (above bottom plate) |
| Radius of gyration | |
| Roll | 26 |
| Pitch | 26 |
| Yaw | 13 |

| | |
|-----------------------|--------------|
| Total weight of ASOP | 451,515 kips |
| Vertical mooring load | 1,350 kips |
| Total displacement | 452,865 kips |

Table 3.12 Weight list at transit draft (35 ft)

| | |
|--------------------------------|--------------------|
| Structural and fixed weight | 98,215 kips |
| Fuel Storage | 0 kips |
| Mooring lines and anchors | 3,000 kips |
| Variable payload | 1,000 kips |
| Water ballast in 8 soft tanks | 172,760 kips |
| Water ballast in ballast tanks | <u>19,647 kips</u> |
| Total weight | 294,622 kips |
| C.G. | 38 ft (above keel) |
| Total displacement | 294,622 kips |

CHAPTER 4 STABILITY

4.1 General

The stability of the ASOP is mainly provided by the six articulated buoys located at each corner of the hexagonal hull. The center column has little contribution for intact stability but provides much needed reserved buoyancy in the damaged condition. The superstructure (topside) is not designed to provide buoyancy for the platform. Although the water plane area is small compared to other types of column stabilized platforms, the large spacing between the buoys gives a considerable amount of restoring force when the platform is heeling (The restoring moment is proportional to the square of spacing between buoys across the corners). On the other hand, the articulation of the buoys raises a unique problem for the stability of the platform which does not exist in fixed column platforms such as semi-submersibles. At certain heeling angles, the buoys at one side rise to a draft where the buoy can not stay upright anymore. In this condition, the buoy will assume a stable equilibrium position that is inclined at a certain heel angle to the vertical and will dramatically lose its contribution to the stability. This can be explained by looking at the vertical force on the universal joints. Figure 4.1 shows the vertical force at the universal joint as a function of the vertical position of the joint. The slope of the curve shows how effectively the buoy contributes to stability. A steeper slope of the curve means a large restoring moment will be created for the same heeling angle. When the vertical distance between the joint and the water line is less than 55 ft and the buoy can not stay vertically anymore, the slope of the curve is reduced dramatically and the buoy is no longer effective to the stability. In addition, once the buoy is totally submerged in the water, it will not provide further restoring force when the platform continues to heel. Also the relative movement of the center of buoyancy of the buoys to the hull during heel reduces the restoring moment. These unique characteristics of the articulated buoy will raise problems for large angle stability of the ASOP. In the following two sections, the intact and damaged stability of the ASOP will be discussed.

4.2 Intact Stability

4.2.1 Stability Criteria

The stability criteria used in the ASOP design is the US Coast Guard rules for mobile offshore drilling units (Code of Federal Regulations, Title 46 -- Shipping, Chapter I, Part 174, Subpart C). The American Bureau of Shipping has very similar rules for mobile offshore drilling units. The major requirements in these rules are:

- 1) The area under the righting moment curve from the angle of 0 to the second intercept of the righting and wind overturning moment curves or the downflood angle, whichever is less, shall be more than 1.3 times greater than the area under the wind overturning moment curve to the same limiting angle.
- 2) The righting moment must be positive for all angles greater than 0 and less than the second intercept angle.

4.2.2 Wind Heeling Moment

The method of wind force and heeling moment calculation is based on the Coast Guard rules. The wind force is sensitive to the shape and projected area of the topside. In this stage of the conceptual study, except for the fuel load and off-loading purpose, the full function of the topside and associate equipment on it is not totally defined. Therefore, in order to reasonably estimate the wind force on the topside of the ASOP, a typical deck of offshore oil production platform is used in this study. The projected area of the deck is listed as follows:

| | Projected Area | Center of pressure (above waterline) |
|--|----------------------|---|
| Above drilling deck (deck house, rig and equipment) | 9428 ft ² | 148 ft |
| Between cellar and main deck | 6186 ft ² | 105 ft |
| Between subcellar and cellar deck: | 3152 ft ² | 69 ft |

At the operational draft, the total wind heeling moment is 218,948 kips-ft for a 100 knot wind, and 54,737 kips-ft for a 50 knot wind. At transit draft (35 ft), the wind heeling moment is 289,642 kips-ft for a 100 knot wind.

4.2.3 Stability at Operational Draft

Figure 4.2 shows the intact righting moment curve and wind heel moment curve as a function of roll angle. The ASOP is at the operational draft (145 ft) and the wind speed is 100 knots (severe storm condition). Figure 4.3 shows the righting moment curve as a function of pitch angle. The righting moment curves for roll and pitch are very similar at small angles but different at larger angles due to the articulation discussed in section 4.1. Because of the large distance between the buoy and the center of the platform, the buoys at one side submerge into water completely at a relative small angle (9.5 degrees in roll), and no further buoyancy force is added by the buoys. Furthermore, the buoys at the other side will not keep vertical after a roll angle of 7.6 degrees and also greatly lose their contribution to the righting moment. Therefore, the righting moment reduces quickly when the roll is beyond 10 degrees and the range of roll angle of positive righting moment is much shorter than that of a conventional fixed column semi-submersible. In order to satisfy the stability criteria, a very large initial stability (or metacentric height) is required to ensure enough area under the righting moment curve. In the design, the ratio of the area under the righting moment curve and the wind heel moment curve is 1.6, which satisfies the stability criteria.

Following is a summary of the intact stability at the operational draft:

| | | |
|---------------------|---------|------|
| Draft | 145 | ft |
| Total Displacement: | 452,865 | kips |
| C.G. (above keel): | 34.5 | ft |
| C.B. (above keel): | 30.9 | ft |
| GMT: | 8.57 | ft |
| GML: | 8.57 | ft |

4.2.4 Stability at Transit Draft

When the ASOP is at transit draft (35 ft), the hexagonal hull contributes to the stability of the platform. The righting moment is extremely large because of the large water plane area and second moment of the hull. Figure 4.4 shows the righting moment arm and wind heeling moment arm (for 100 knot wind speed) as a

function of roll angle. The stability of the ASOP in the transit draft meets the stability criteria.

Following is a summary of the intact stability at the transit draft:

| | | |
|---------------------|--------|------|
| Draft | 35 | ft |
| Total Displacement: | 294622 | kips |
| C.G. (above keel): | 37.9 | ft |
| C.B. (above keel): | 17.5 | ft |
| GMT: | 280.9 | ft |
| GML: | 280.9 | ft |

4.2.5 Free Surface Effects

At the operational condition, the soft storage tanks and most of the ballast tanks will be 100 percent full. Hard tanks will have a free surface most of the time, but those tanks have a relatively small free surface area and the reduction of the stability caused by the free surface effect is small. Assuming all the hard tanks and two of the ballast tanks have free surface, the reduction of the metacentric height (GMT) is 0.5 feet, or 6%.

At transit mode, the fuel storage tanks are either empty or 100 percent full. Free surface exists only in the ballast tanks and it has little influence on the stability due to the extreme large metacentric height. Assuming all the ballast tanks have free surface, the reduction of the height is only 0.7 feet, or 0.25%.

4.3 Damaged Stability

The damaged stability is a challenge to the ASOP concept due to its unique configuration. It is a key factor in determining the compartmentation of the hull and the buoys. Because of the large moment arm, any damage of the buoys and fuel storage tanks can cause considerable overturning moment, and in turn, cause large heeling angles and even capsize. The following are the possible damage conditions:

- 1) The buoys are damaged and flooded.
- 2) The center column is damaged and flooded.

- 3) The fuel storage tanks and the ballast tanks are damaged and flooded.
- 4) The universal joints are broken.

In our design, three criteria are established for damaged stability of the ASOP. They are as follows:

- 1) The platform will remain operational if any one buoy is damaged. The flooding will be limited to one third of the buoy's total volume. The stability must satisfy the Coast Guard rules and ABS rules for damaged condition.
- 2) The platform will remain operational if the center column is damaged. The flooding condition and damaged stability follows the Coast Guard rules and ABS rules .
- 3) In case any one universal joint is broken, or any one fuel storage tank is flooded, the platform will remain afloat with the topside above water line.

In order to satisfy the first and second criteria, each buoy is divided into 12 compartments by two horizontal watertight flats and two vertical watertight bulkheads, and the center column is divided into 16 compartments (Figure 4.5). According to the rules, four compartments (shadowed compartments in Figure 4.5) of a buoy may be subject to simultaneous flooding, and two of the compartments of the center column at the water line may be subject to simultaneous flooding. The damaged stability requirement of the Coast Guard and ABS is similar to the intact stability requirement except that the wind speed is reduced from 100 knots to 50 knots. Figure 4.6 shows the righting moment curve and wind heeling moment curve (50 knot wind speed) when the buoy is flooded. The damage stability satisfies the requirements of the Coast Guard and ABS. The flooding will also cause a heel of 2.1° and a draft increase of 1.9 ft. In the case of damage to the compartments in the center column, flooding will cause a change of draft about 3.7 ft, and a heel of about 0.35° . The flooding of the center column does not influence the stability because the contribution of the center column to stability is negligible, and the flooding is practically equivalent to adding more weight to the platform.

When a buoy is lost due to the failure of the universal joint and safety chains, an overturning moment applied suddenly will cause the platform to heel dynamically.

The maximum dynamic heeling can be much greater than the heeling when the platform reaches static equilibrium. Model tests showed that the maximum dynamic heeling angle is 1.5 times larger than the static heeling angle. The center column plays a important role in this condition by providing buoyancy and righting moment at large angles of heel. The equilibrium position of the platform after a buoy lost is:

| | |
|-----------------|----------|
| Draft increase: | 26.8 ft |
| Heeling angle: | 33.7 deg |

If one of the tanks in the lower hull is damaged, the most severe condition will occur if that tank is one of the soft tanks at the outside ring and full of fuel. The net weight gain by replacing the fuel in the tank with water is about 2.256 kips. The equilibrium position of the platform after the damage is:

| | |
|-----------------|----------|
| Draft increase: | 5.0 ft |
| Roll: | 1.47 deg |
| Pitch: | 6.16 deg |

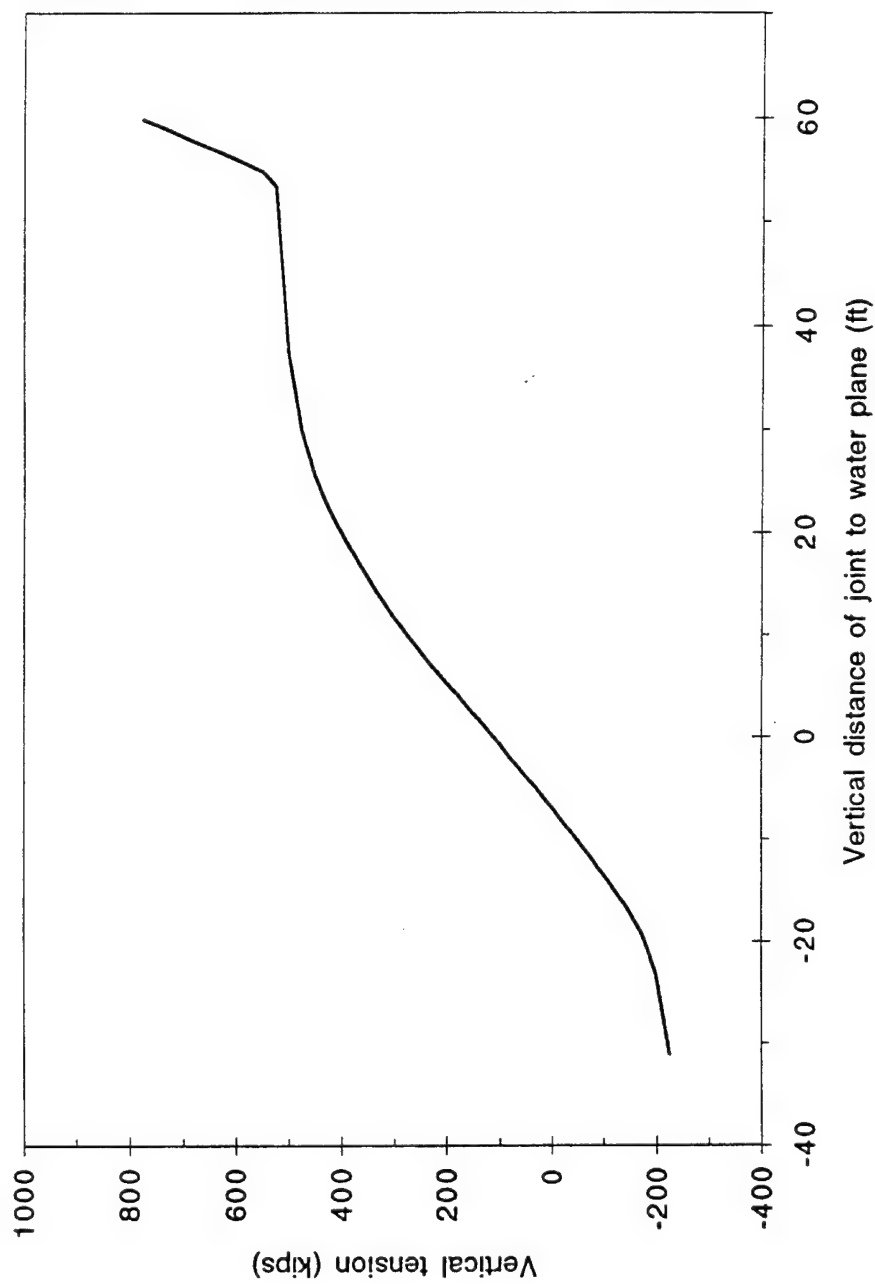


Figure 4.1 Vertical force at universal joint as a function of the vertical distance of joint to water plane (positive if the joint is under water)

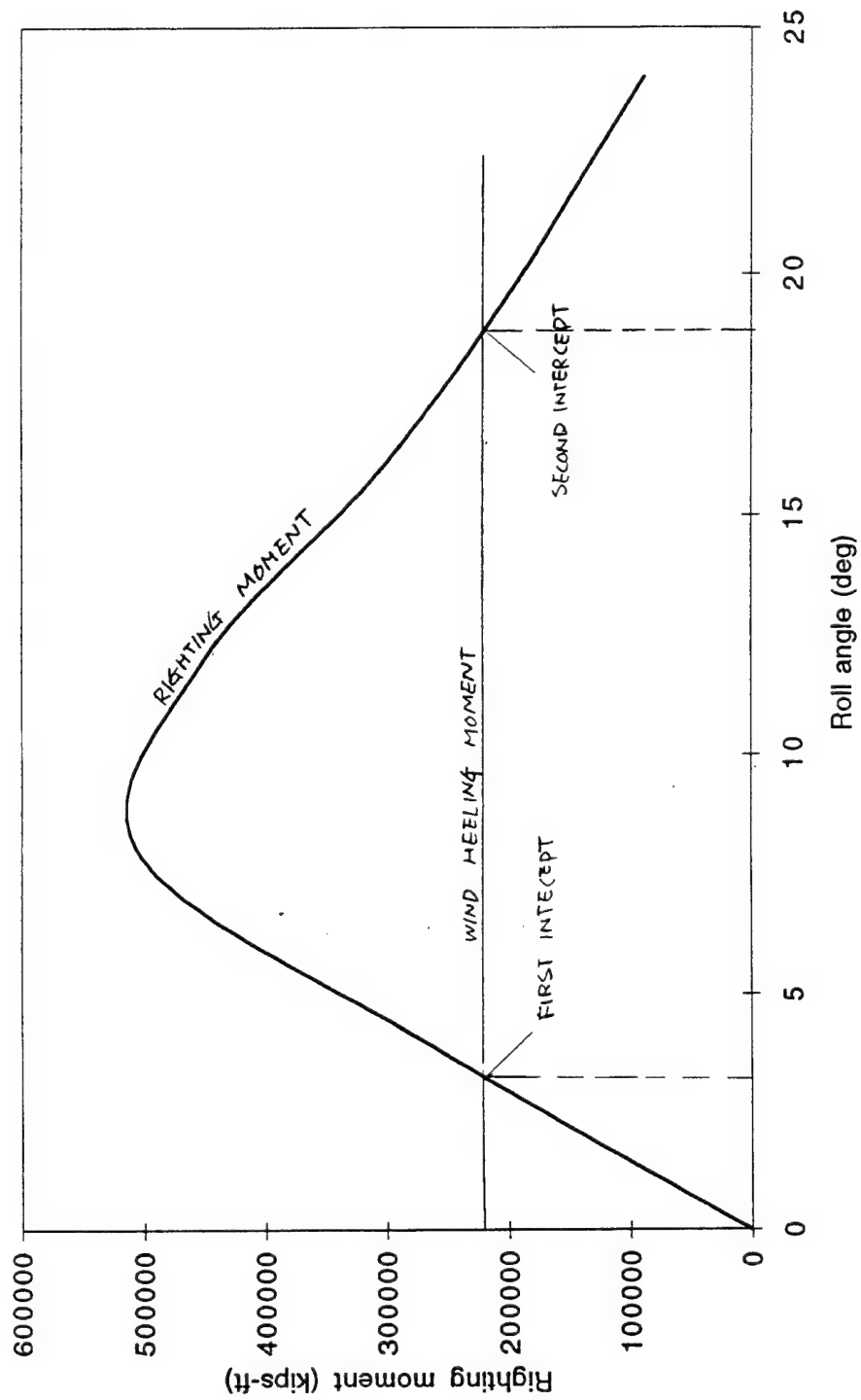


Figure 4.2 The ASOP intact stability curve (roll) at operational draft

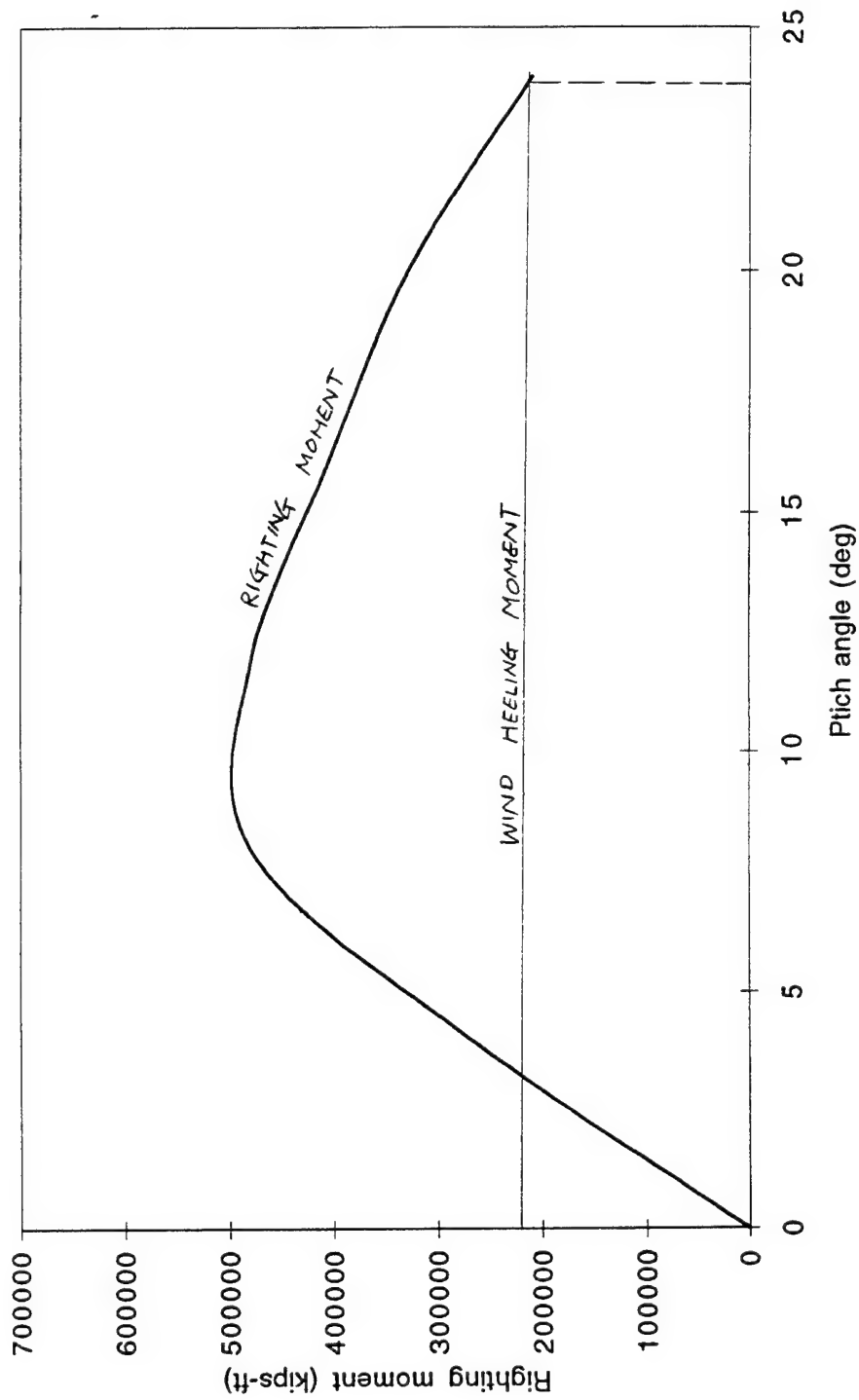


Figure 4.3 The ASOP intact stability curve (pitch) at operational draft

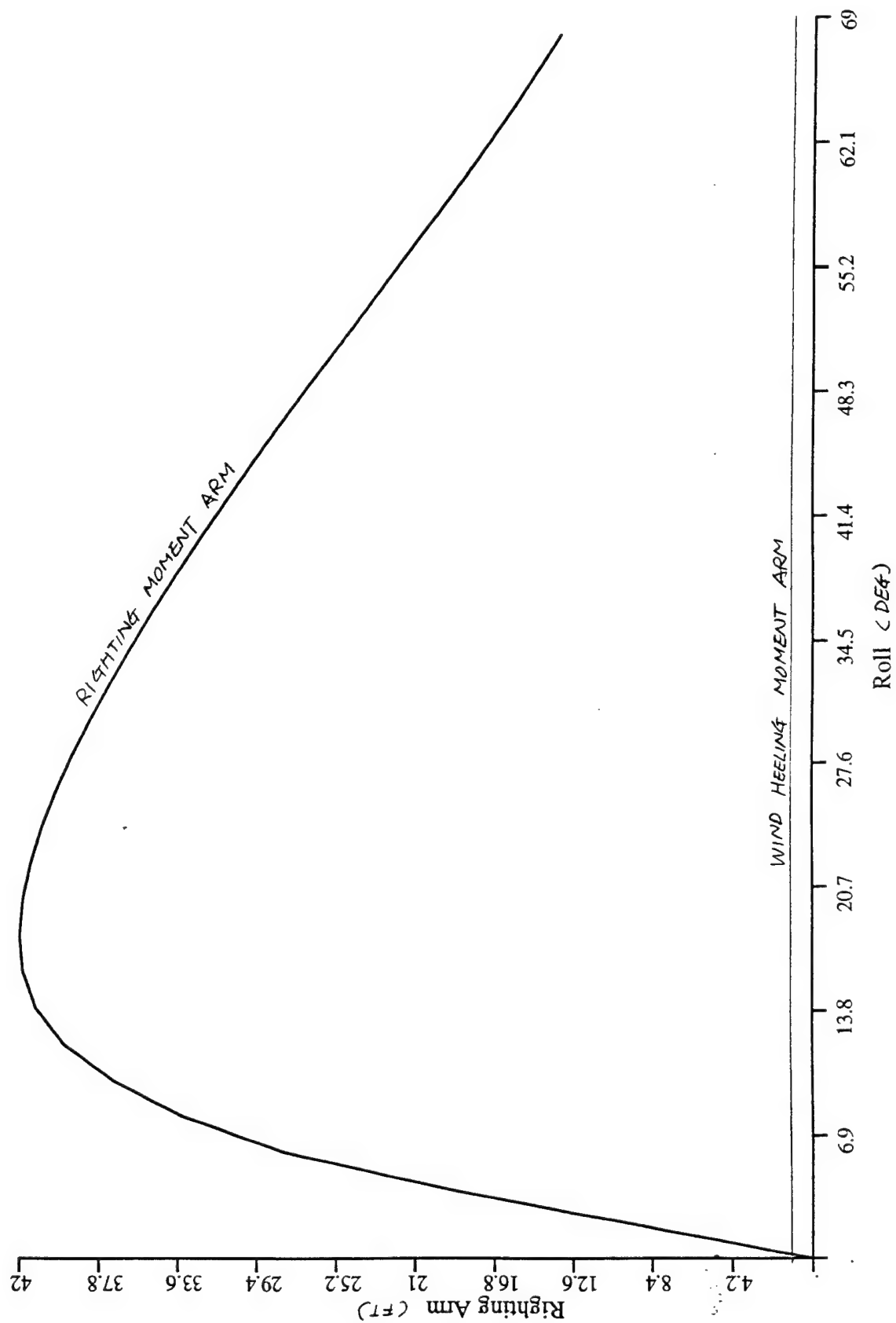


Figure 4.4 The ASOP intact stability curve at transit draft

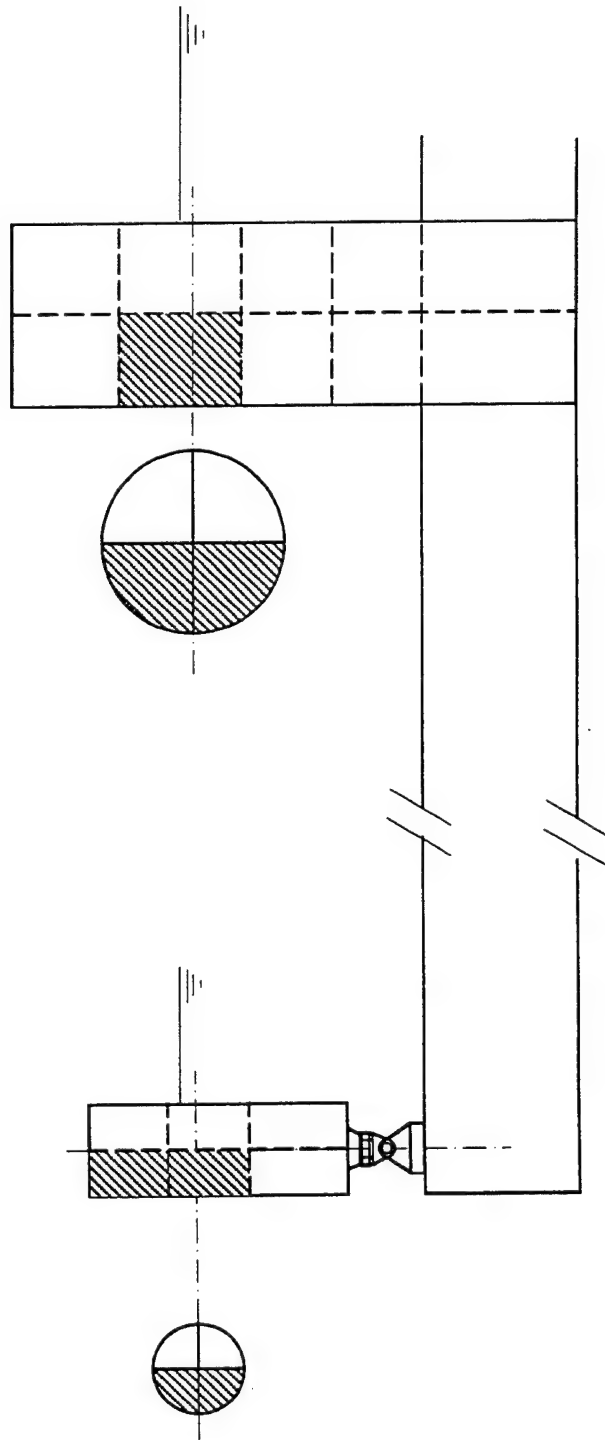


Figure 4.5 The location of the compartments subjected to flooding

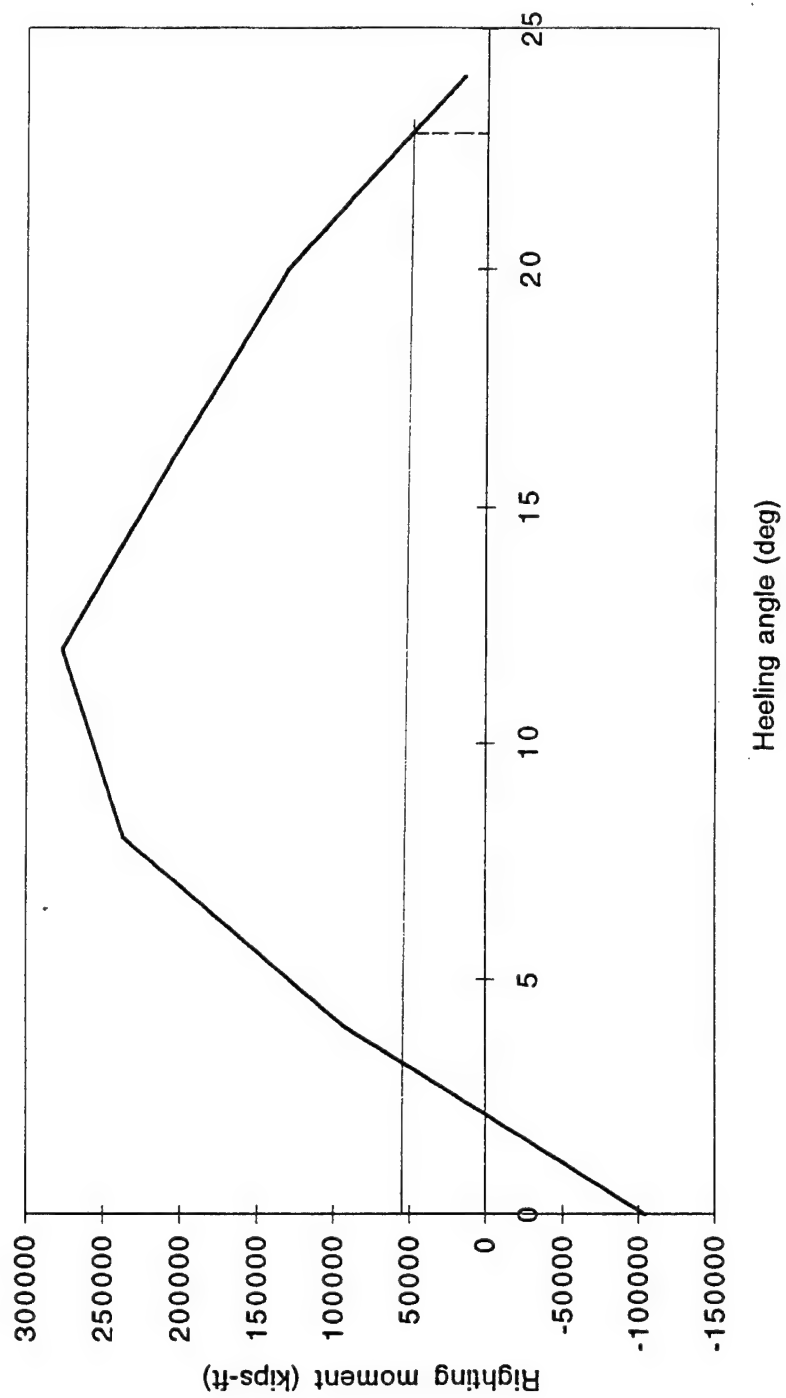


Figure 4.6 The ASOP damaged stability curve (buoy damaged)

CHAPTER 5 SEAKEEPING ANALYSIS

5.1 General

The motion of the ASOP in regular and random waves has been analyzed. At the operational draft, the platform is very stable even in severe wave conditions. The main hull is placed 95 ft below water (145 ft draft) and attracts much less wave force than that of a surface vessel. Furthermore, introducing articulation de-couples the rotational degree of motion of hull and buoy and, in turn, reduces the wave forces transmitted from the buoys to the main platform.

Linear diffraction analysis was performed for the main hull (hexagonal hull and center column) of the platform to obtain hydrodynamic coefficients such as wave exciting force, added mass and wave damping. Figure 5.2 shows the mesh generated for the diffraction analysis. The buoys were considered as slender bodies and the wave forces on them were predicted by Morison's equation, which includes an inertial force proportional to the water particle acceleration, and a nonlinear drag force proportional to the relative velocity squared. A typical six point mooring system is used for the station keeping of the platform. Figure 5.1 shows the stiffness of the mooring system. The water depth is assumed to be 700 ft. The motion of platform and buoys, together with the force on the universal joint and mooring line tension were analyzed both in frequency domain and time domain. A seven body coupled analysis, instead of a conventional single rigid body analysis, was used because the articulation allows relative motions between the hull and the buoys. All the analyses were performed with the computer program MOSES (Multi-Operation Structural Engineering Simulator), which was developed by Dr. R. Nachlinger of Ultramarine, Inc. in consultation with MEH.

In addition to the articulated cylindrical buoys, other buoy configurations and types of connections were also analyzed in order to fully understand the roles of buoys and the articulation in the global motion of the ASOP. They are:

- 1) The buoy is simply fixed to the hull which is equivalent to a column mounted on the hull. The objective was to find out whether the motion of the ASOP was improved by introducing articulation and allow the buoy to move in three rotational degrees of freedom.

2) The buoy is connected to the hull by a linear spring to further de-couple the motion of hull and buoy, and to reduce the force transmitted to the hull. The stiffness of the spring was 45 kips/ft.

3) Changing the buoy shape from cylindrical to hourglass. The buoy diameter was reduced linearly from 30 ft, at 30 ft below water line, to 22 ft at water line, and was linearly increased back to 30 ft at the top of buoy (30 ft above water line). The objective was to reduce the dimension of buoy near the water line and hence reduce the wave force on the buoy.

4) The center column is replaced by a jacket type structure to reduce the wave force on the main hull. Meanwhile, the diameter of the buoys was increased from 30 ft to 39 ft so that the total water plane area remain unchanged.

The detailed description of the above buoy configurations and their mass properties can be found in the model test report from Offshore Model Basin (OMB), "Model Studies of Articulated Stable Ocean Platform, Preliminary Report No. OMB-95-214-1".

5.2 Natural Periods

The natural periods of the platform were obtained by time domain free decay simulation. The analysis indicated that the natural periods in surge, heave and pitch were 214.2, 88.0 and 68.2 seconds, respectively. Those natural periods are far beyond the range of wave energy thus the motion at the wave frequency is expected to be small. However, the buoys have a pitch natural period of 14.1 seconds which is within the frequency where wave energy exists. Although it is better to have the natural period of the buoy out of the wave energy range, in order to do so, the buoy will have a much larger weight which in turn will reduce the contribution of the buoys to the stability of the platform. This is a typical case of compromising between motion and stability. Figures 5.3 to 5.6 show the simulated surge, heave, pitch and buoy pitch free oscillations .

5.3 Frequency Domain Analysis

The response amplitude operators (RAO, the motions or force amplitude correspondence to unit amplitude wave) of the motion, connector force, and mooring line tension were calculated in the frequency domain. Nonlinear viscous forces were linearized using equivalent energy method (the work done by nonlinear drag force in a wave period is equivalent to the work done by the linearized drag force). The wave period range was from 5.5 seconds to 25 seconds. Two wave headings --0 and 90 degree -- were studied. The results shows little difference between the two headings due to hull symmetry. Therefore, only the results for 0 degree wave heading are presented in this report.

Figures 5.7 to 5.9 show the surge, heave and pitch RAO of the platform, respectively. Figure 5.10 shows the vertical force at the universal joint (buoy #1 in Figure 6.2). Figure 5.11 shows the mooring line tension (ML1 in Figure 6.2). The results indicate that there were improvements in the forces at the buoy--hull connection by using spring connection and hourglass shaped buoys, but motion and mooring line tension were very similar among all the configurations. Also, there was no significant difference in the overall motion and mooring line tension between the platforms with fixed buoys and articulated buoys. The surge was slightly improved (less than 4%) by using articulation but the pitch motion was increased compared to the fixed buoys configuration. In general, improvement of motion by using articulation, spring connection and changing buoys shape was insignificant. Because of the large under water volume of the lower hull, the motion of the ASOP is dominated by the mass of the hull and the wave force on the hull, not the buoys. For example, in the regular wave with 12 second period, the wave force on all six buoy was only 17.60% of the wave force on the hull in surge, 5.27% in heave and 0.77% in pitch. Introducing articulation and other buoy configurations did not change the wave force on the hull significantly hence having little effect on the motion of the platform. Compared to the cylindrical buoys, the hourglass shaped buoys reduced the vertical force transmitted to the hull by 50% (60 kips) in the regular wave with 12 second wave period, but that only changed the total heave force on the hull by 1.8% and was not efficient in improving the motion of the platform.

The model test results in regular waves are also presented in those figures. We saw good agreement between the numerical analysis and the model test in heave response, vertical force at the buoy - hull connection and mooring line tension. There was some discrepancy in the surge and pitch response (about 20% difference) but the trend of the response varying with wave frequency was very similar. The model test also indicated that there was no significant difference in motion and mooring line tension among the different configurations.

5.4 Time Domain Simulation

Like other compliant type offshore platforms such as the semi-submersibles which have very long natural periods, the ASOP was dominated by slow drift motions. The slow drift motion is the motion of a platform at its natural frequencies due to nonlinear wave forces. One of the nonlinear wave forces is the slow drift force which is generated by interactions between wave components of different periods. Although an order of magnitude smaller than the wave frequency force, the drift force has very long periods and can cause resonant response of the platform. Usually the magnitude of slow drift motion of the platform is much larger than that of waves frequency motion and is very important for mooring system design. Another typical nonlinear force is the velocity squared drag force. Frequency domain analysis predicts the wave frequency (linear) motion with accuracy, but it may give gross error for the drift motion because the nonlinearities can not be included in the analysis. Therefore, time domain analysis, which can include the nonlinear effects, is usually used to predict the motion of platform in random waves.

The motion of the ASOP was simulated in time domain for two extreme wave conditions -- a 10 year storm and a 100 year storm. The waves were assumed to be unidirectional (long-crested) and the wave heading was 0°. The wave energy distribution followed the JONSWAP spectrum formula with appropriate significant wave height, peak spectrum period and over-shooting parameter. For the 10 year storm, the significant wave height was 20 ft, peak period was 11 seconds and overshooting parameter was 2. For the 100 year storm, the significant wave height was 39 ft, peak period was 14.1 seconds and overshooting parameter was 2. Wind and current force, which are usually modeled as steady forces and only cause a steady offset of the platform, were not considered in the analysis. The duration of

the simulation was one hour, and the time step was 0.5 second. The Newmark-Beta integration scheme, which is a unconditional stable with second order accuracy, was used in the simulation. After the simulation, the statistics of the time series, including motion of the platform, force on the buoy-hull connection and mooring line tension were obtained. In addition, to better understand the motion characteristics, the high frequency and low frequency filter was used to separate the wave frequency response and slow varying response and the statistics for both components were obtained.

Figures 5.12 and 5.13 show the numerically generated wave and its energy spectrum. Figures 5.14 to 5.19 show the simulated time history and spectra of the ASOP's surge, heave and pitch response. The simulation has also been done for the same platform with fixed buoys instead of hinged buoys in order to see the effects of articulation. Tables 5.1 and 5.2 list the statistics of the numerical simulation together with the model test results.

Both the numerical and model test results show that there are significant slow drift motions for the ASOP in random waves. For the 10 year storm condition, the numerical simulation in general agrees with the model test results except that the slow drift heave motion was smaller than that of the model test. For the 100 year storm condition, although wave frequency responses were very close, there were some discrepancies in mean and slow drift responses between simulation and model test. This shows that accurate prediction of the nonlinearities in numerical analysis is still a challenge. By fixing the buoys to the hull, the slow drift motion of the platform was greatly reduced. The reason for this was that the large angle pitch motion of the buoys introduced more nonlinear forces into the system and, in turn, created larger drift motions. The model test results gave similar conclusions but the reduction of the drift motion by fixing the buoys was insignificant.

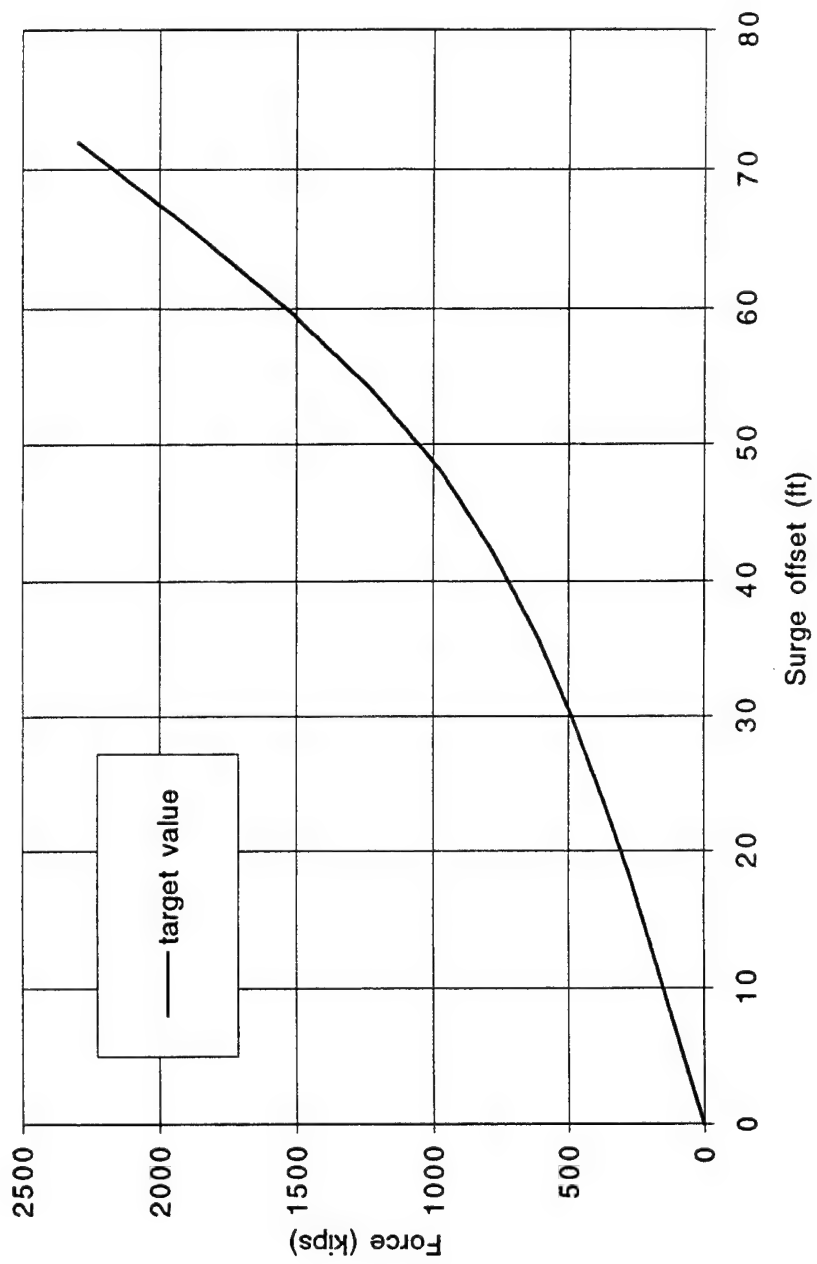


Figure 5.1 Mooring stiffness in surge direction

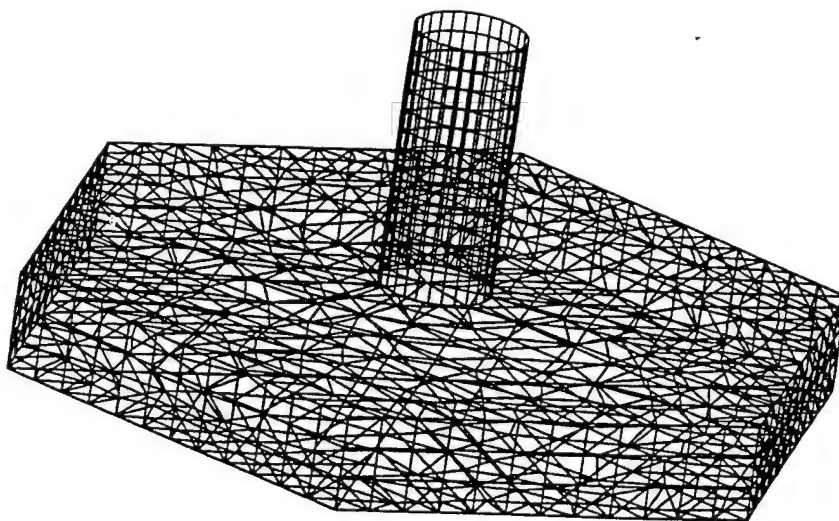
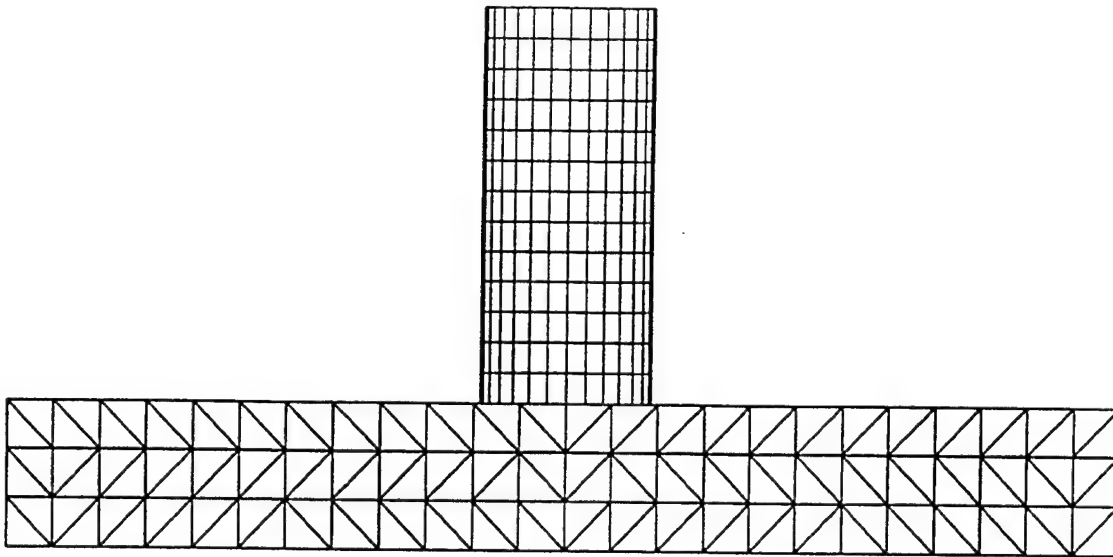


Figure 5.2 Mesh generated for the diffraction analysis

Figure 5.3 The ASOP surge free decay simulation

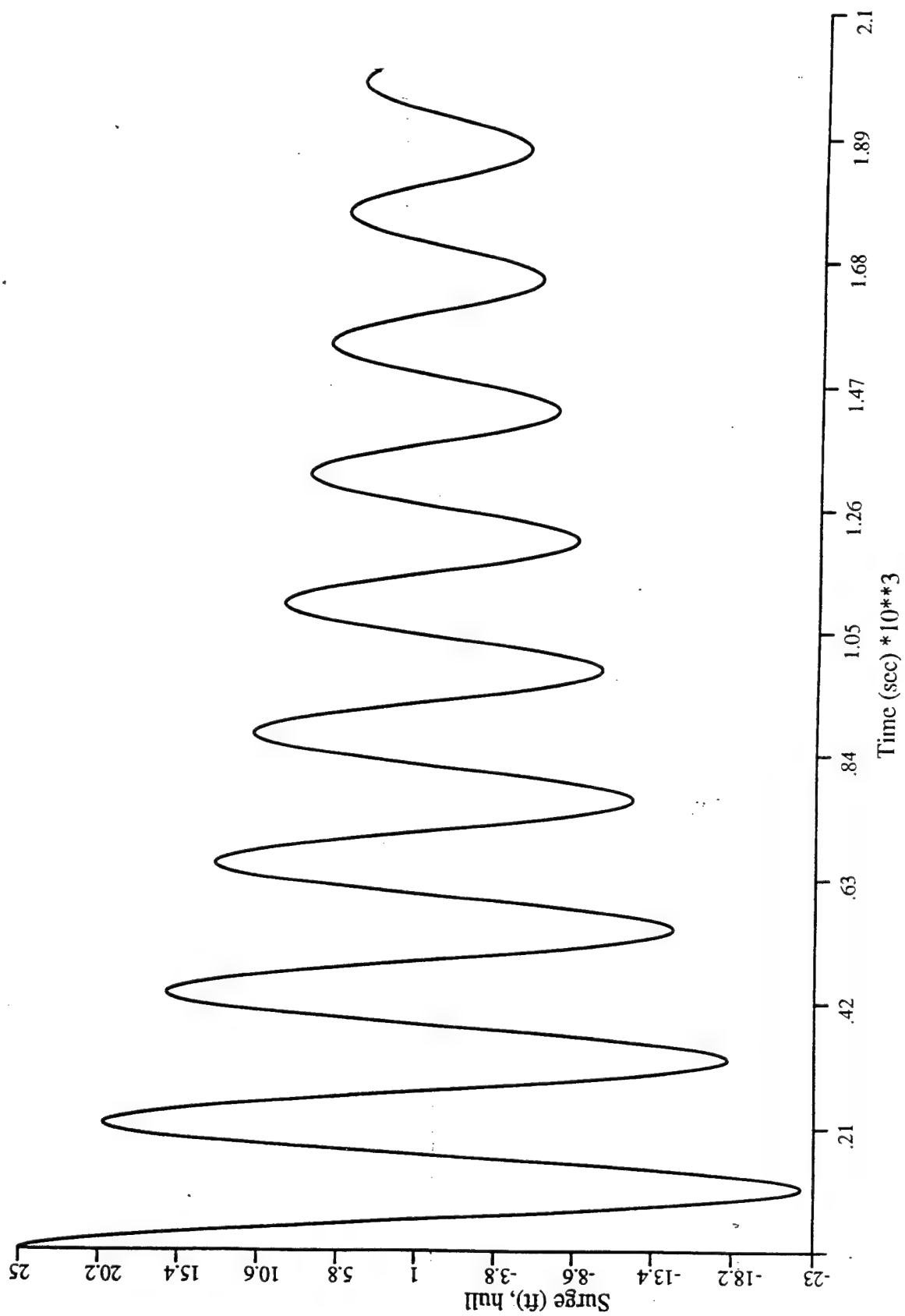


Figure 5.4 The ASOP heave free decay simulation

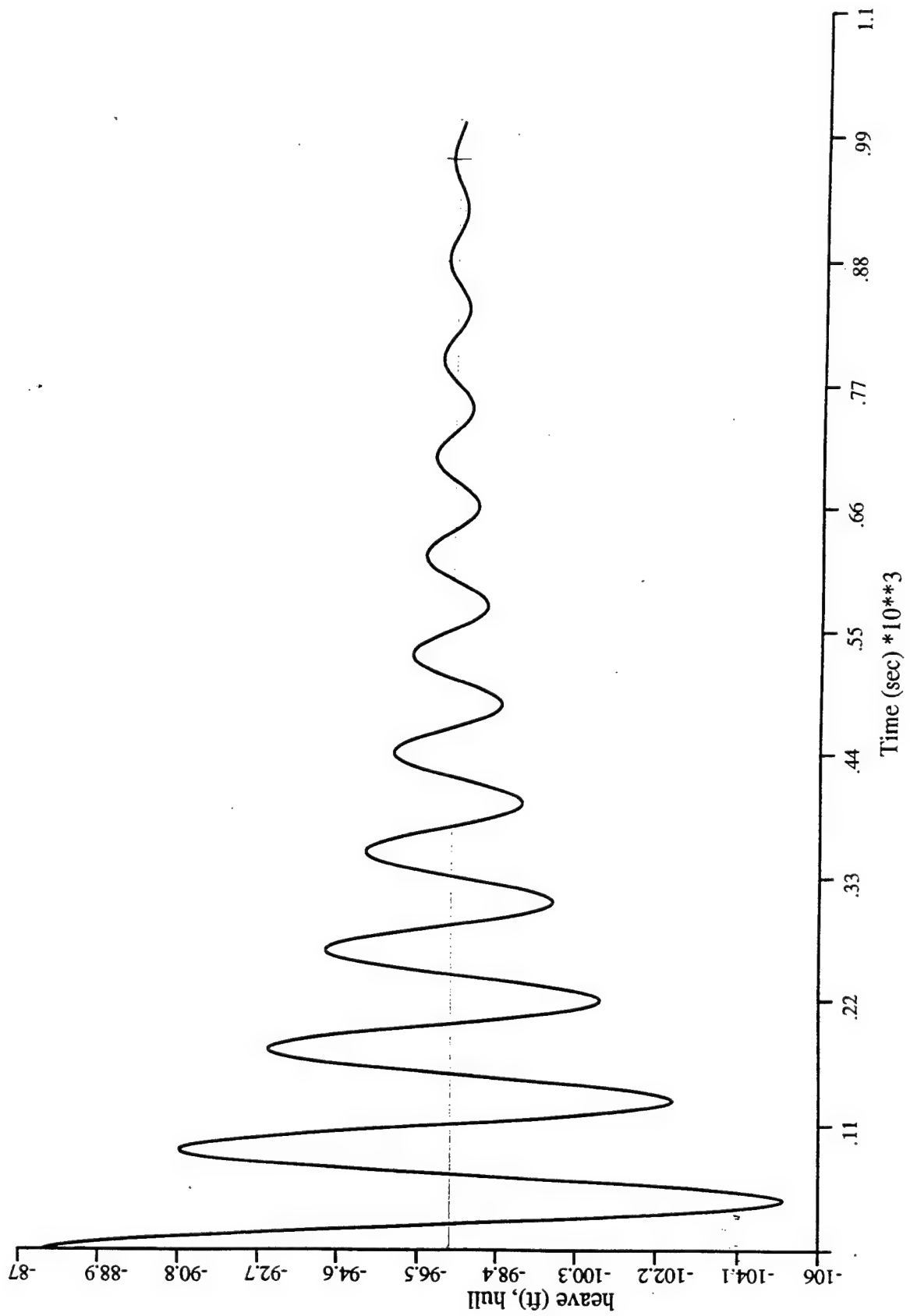


Figure 5.5 The ASOP pitch free decay simulation

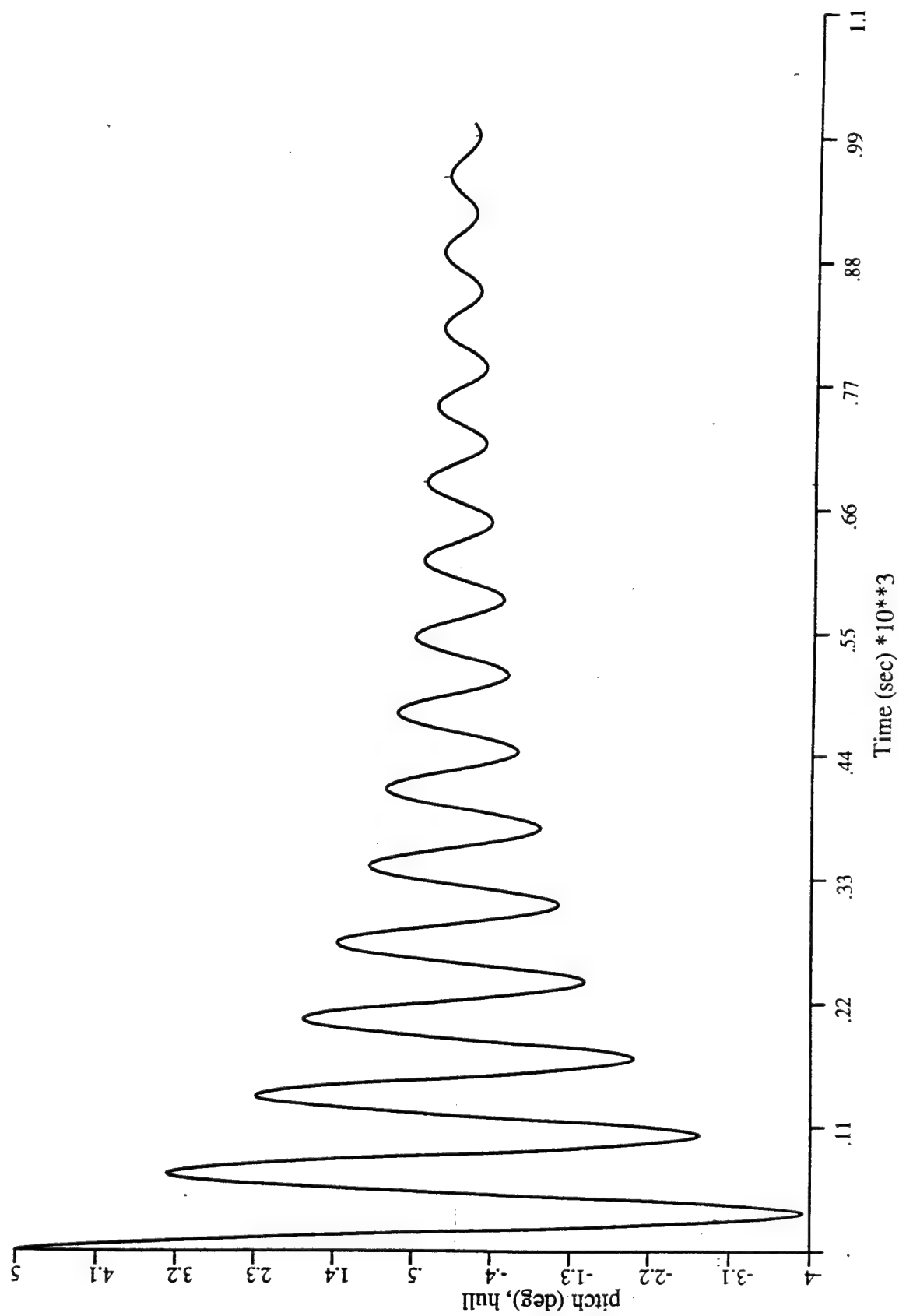
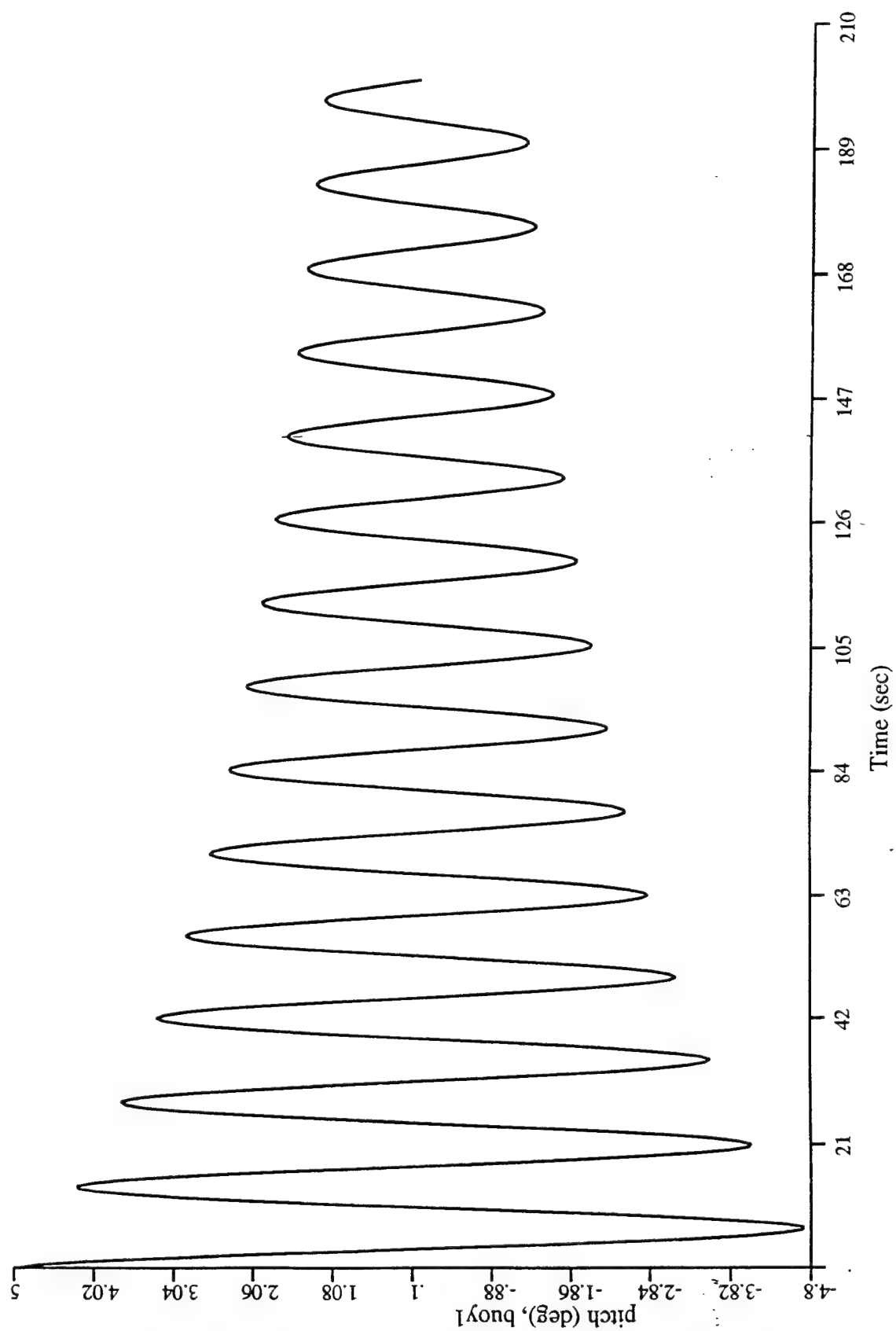


Figure 5.6 The buoy pitch free decay simulation



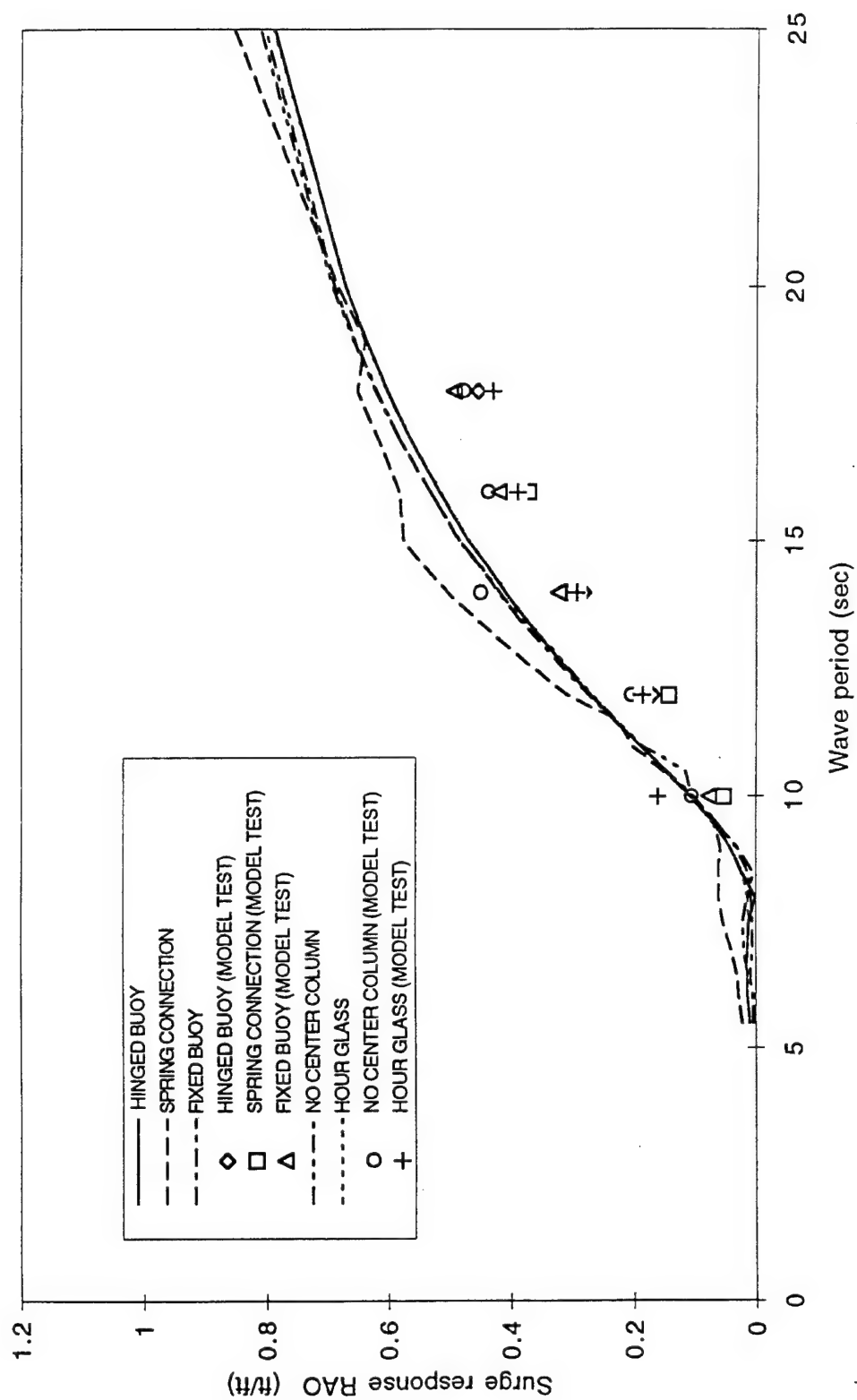


Figure 5.7 Frequency domain analysis. Surge response RAO

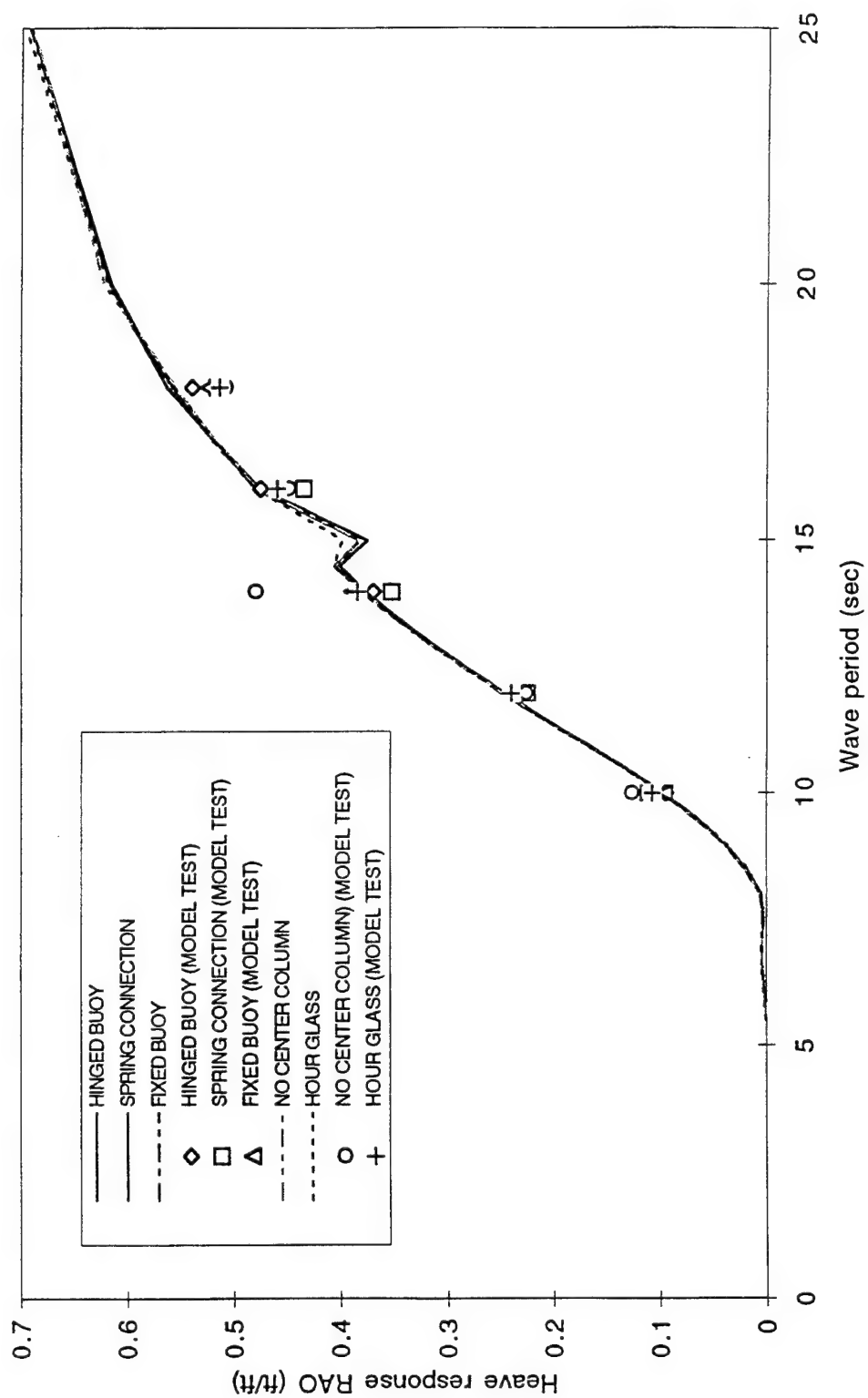


Figure 5.8 Frequency domain analysis. Heave response RAO

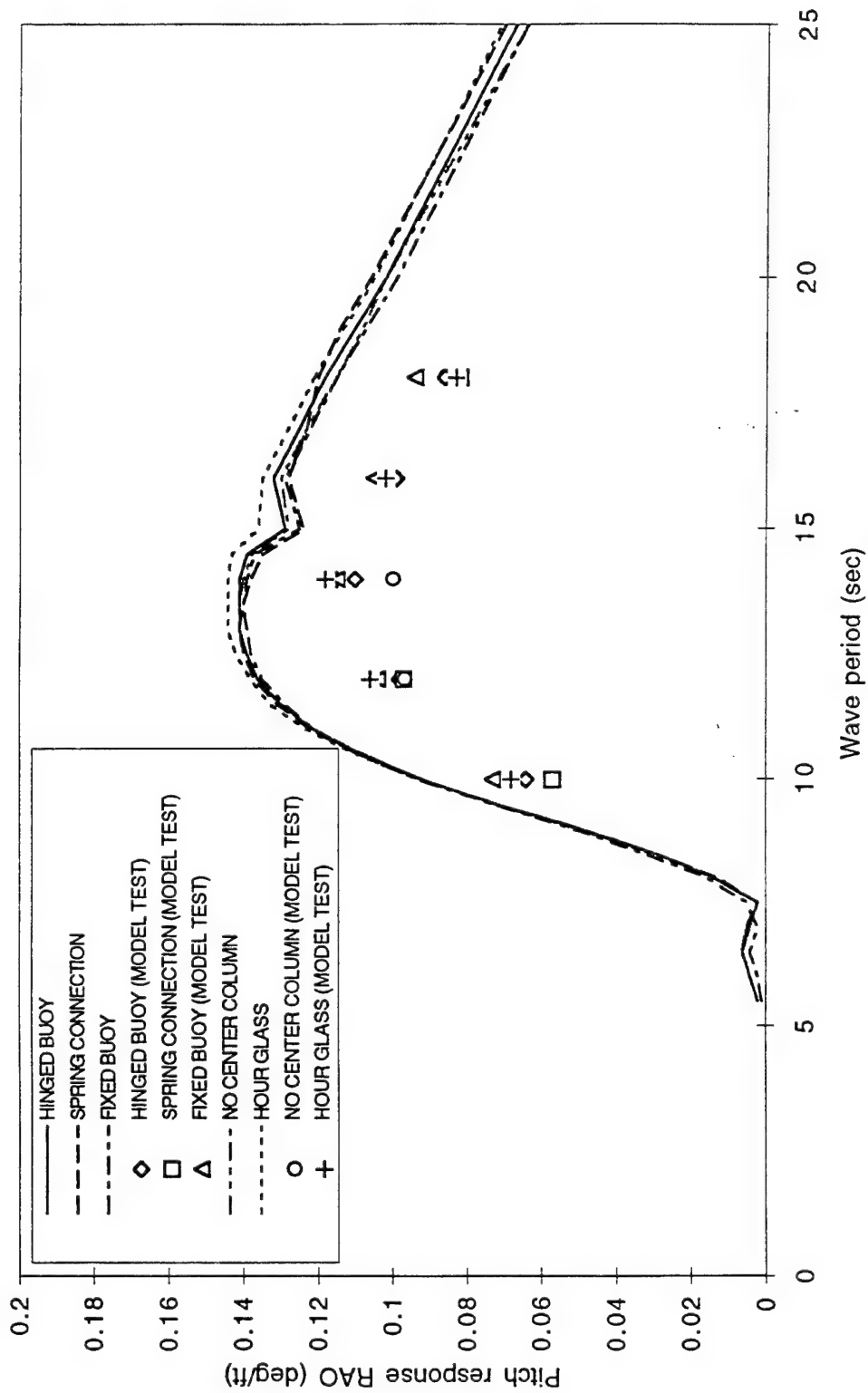


Figure 5.9 Frequency domain analysis. Pitch response RAO

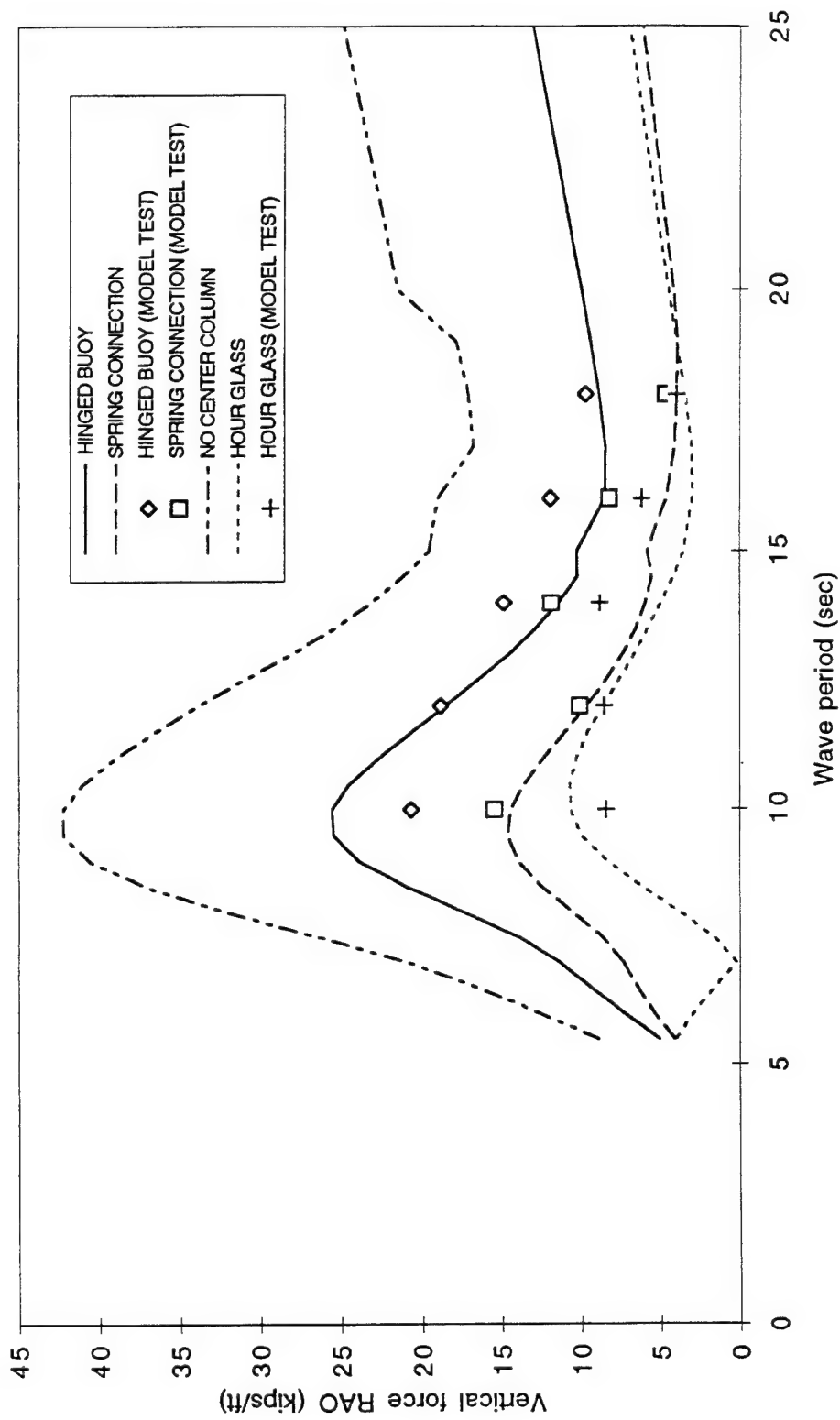


Figure 5.10 Frequency domain analysis. Vertical force on the buoy-hull connection

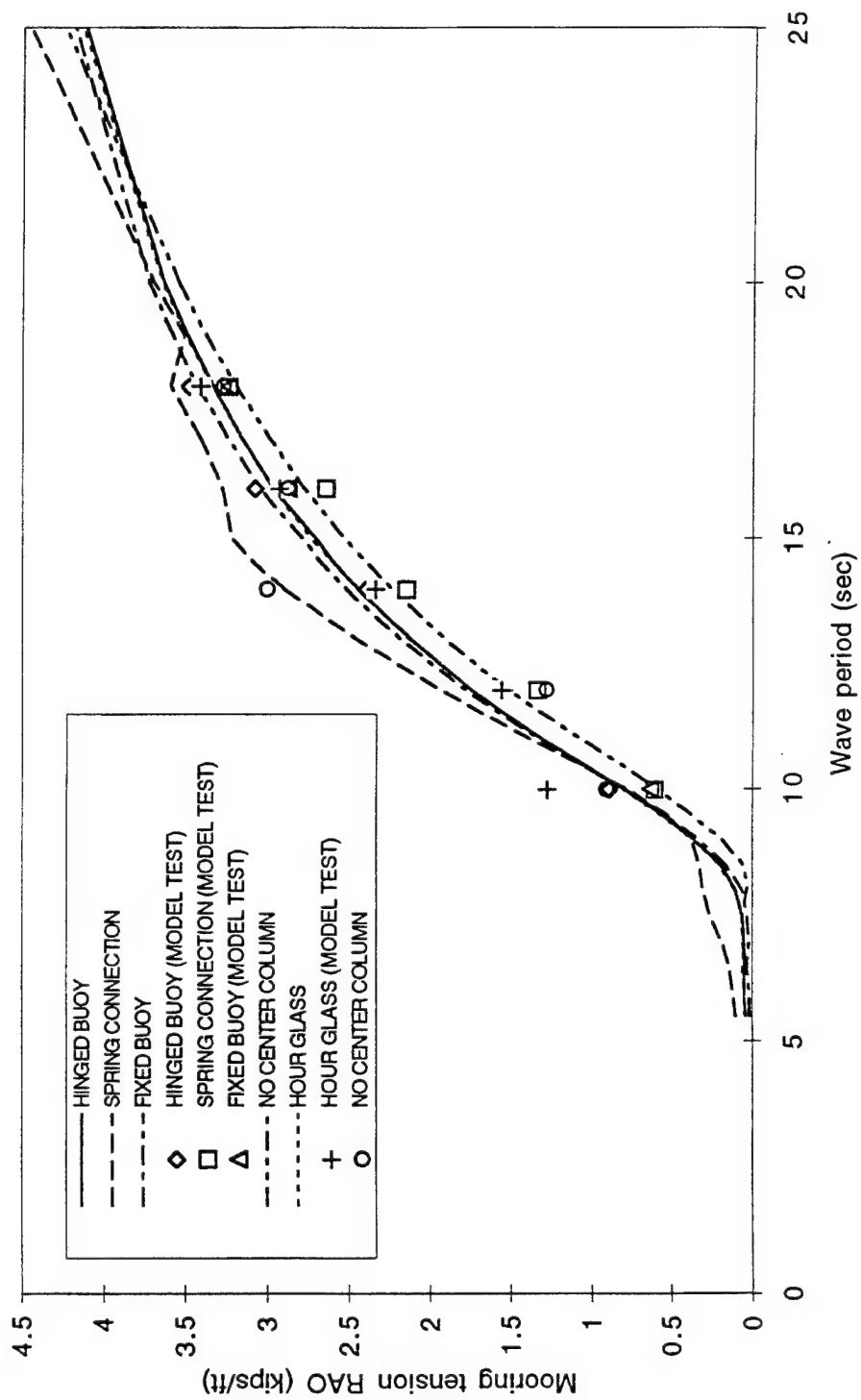


Figure 5.11 Frequency domain analysis. Maximum mooring line tension RAO

Figure 5.12 Time series of the simulated random wave elevation (100 year storm)

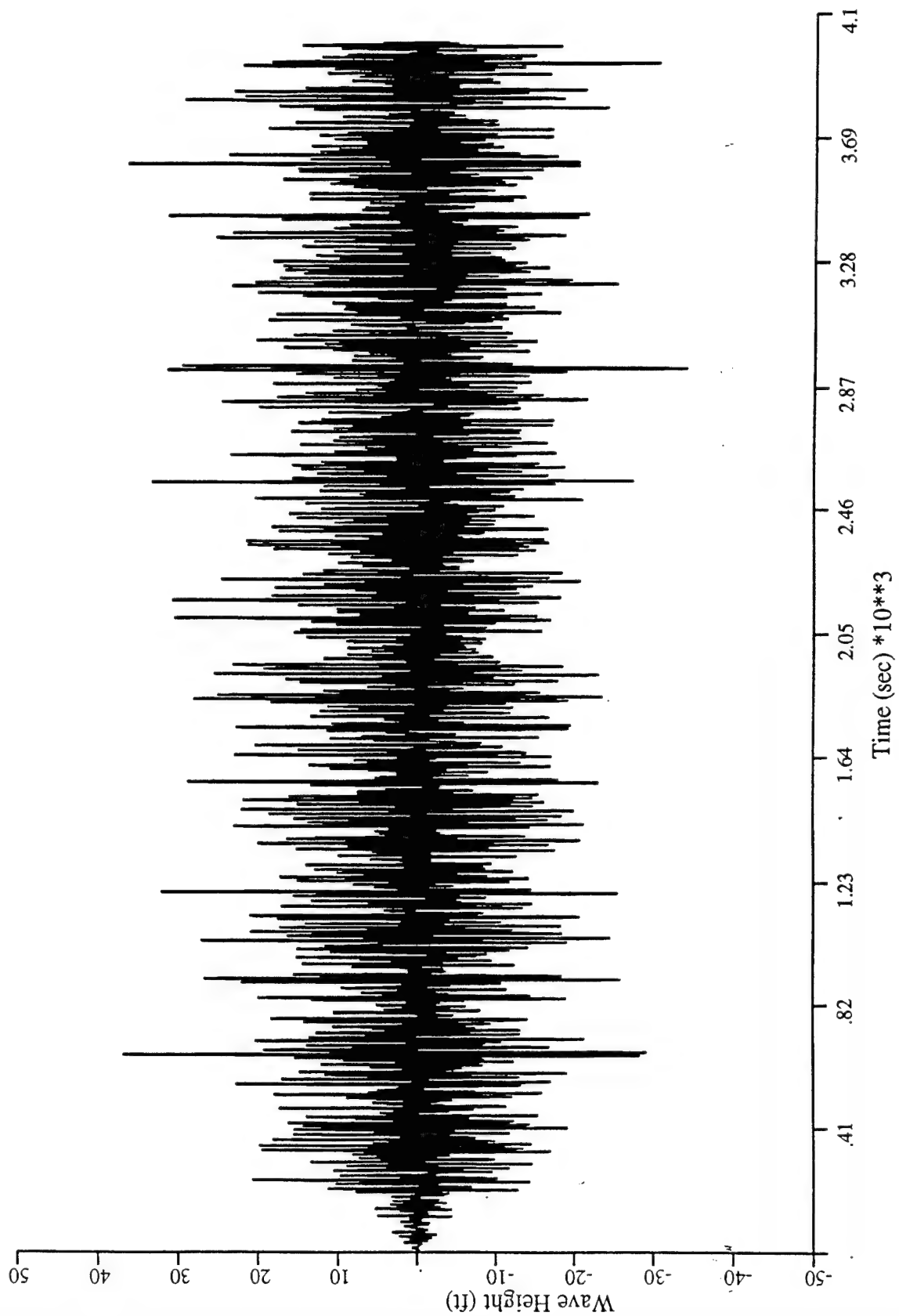


Figure 5.13 Energy spectrum of the simulated random wave (100 year storm)

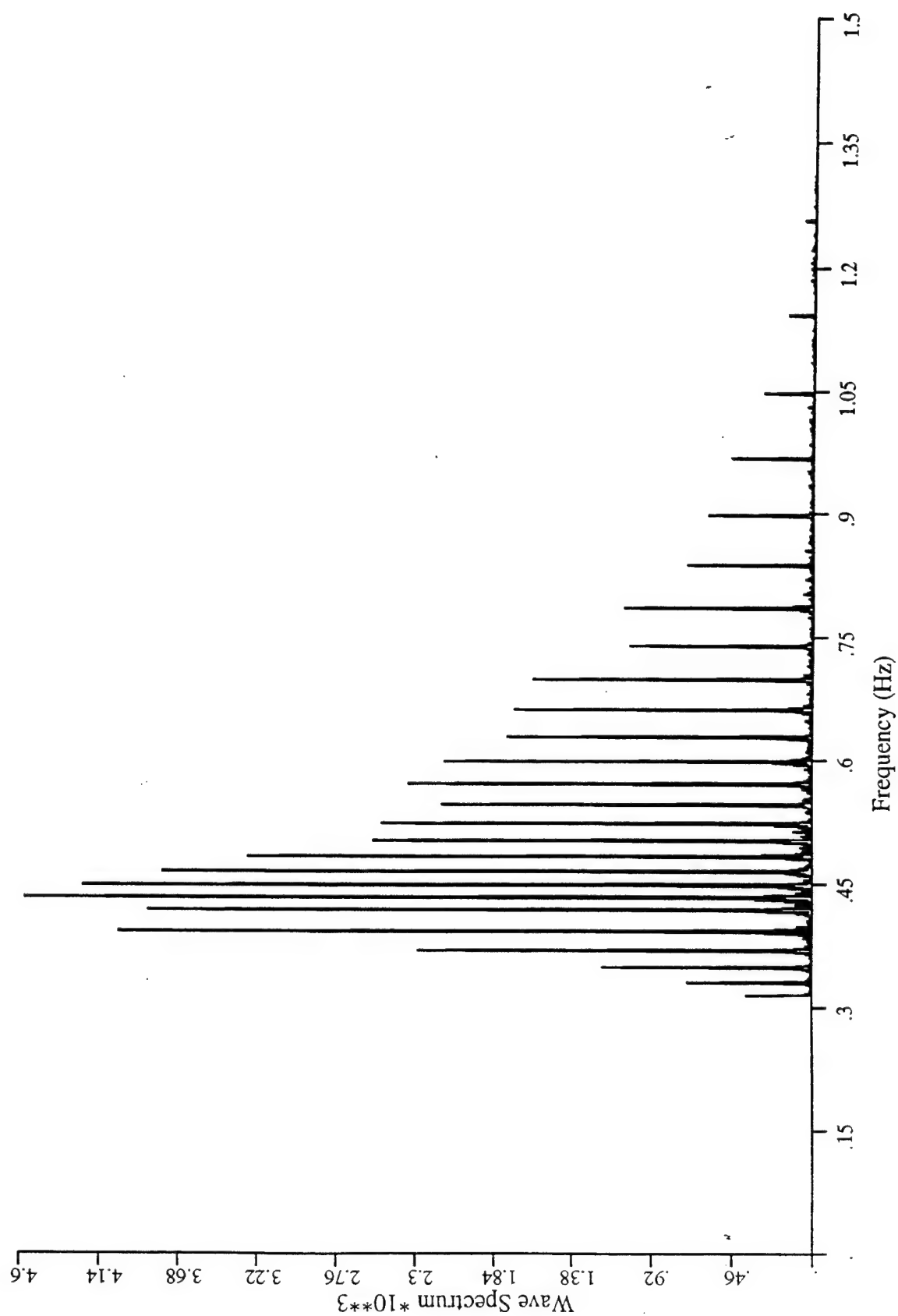


Figure 5.14 Time series of the simulated surge motion of the ASOP in 100 year storm.

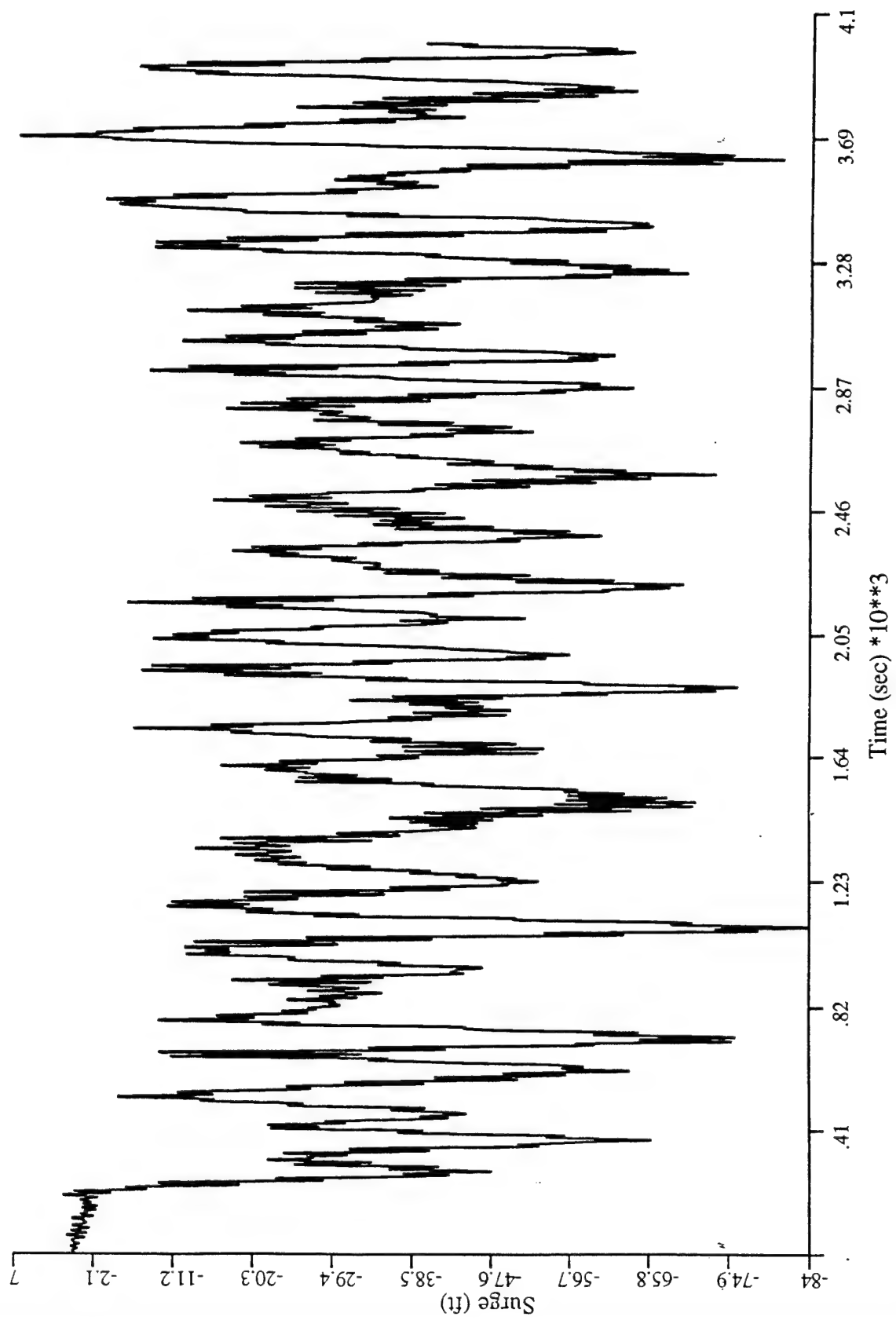


Figure 5.15 Energy spectrum of the simulated surge motion of the ASOP

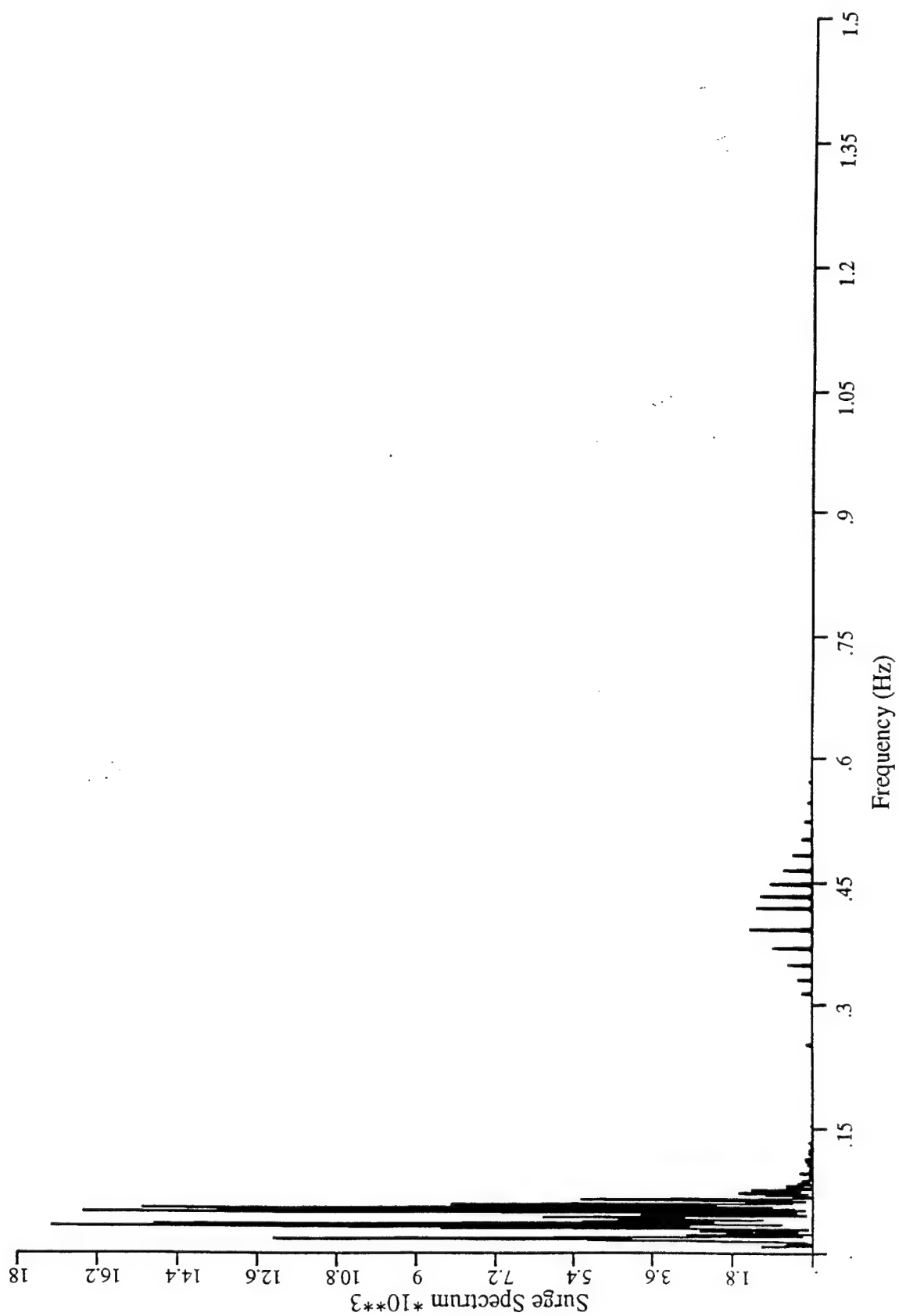


Figure 5.16 Time series of the simulated heave motion of the ASOP in 100 year storm.

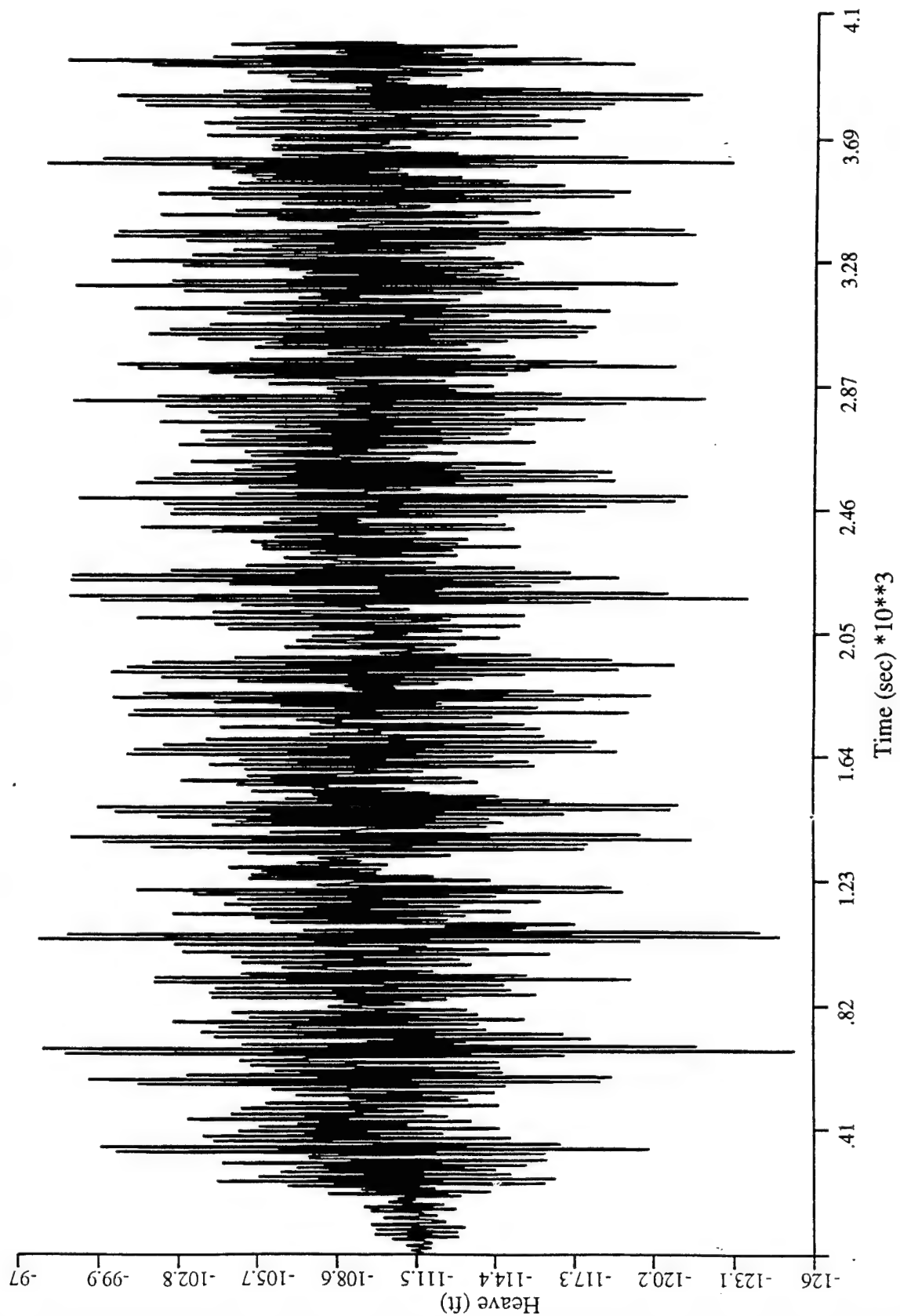


Figure 5.17 Energy spectrum of the simulated heave motion of the ASOP

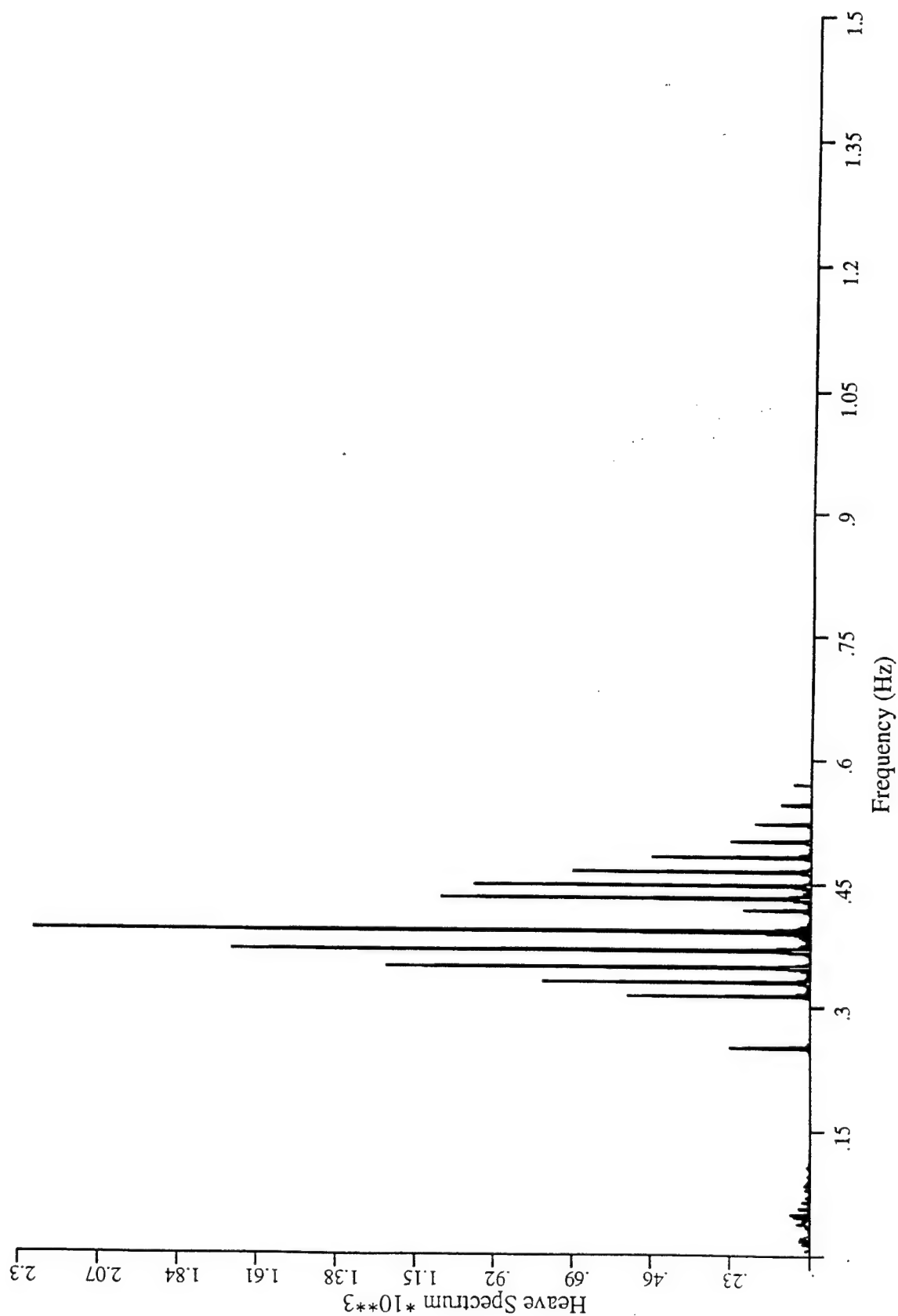


Figure 5.18 Time series of the simulated pitch motion of the ASOP in 100 year storm.

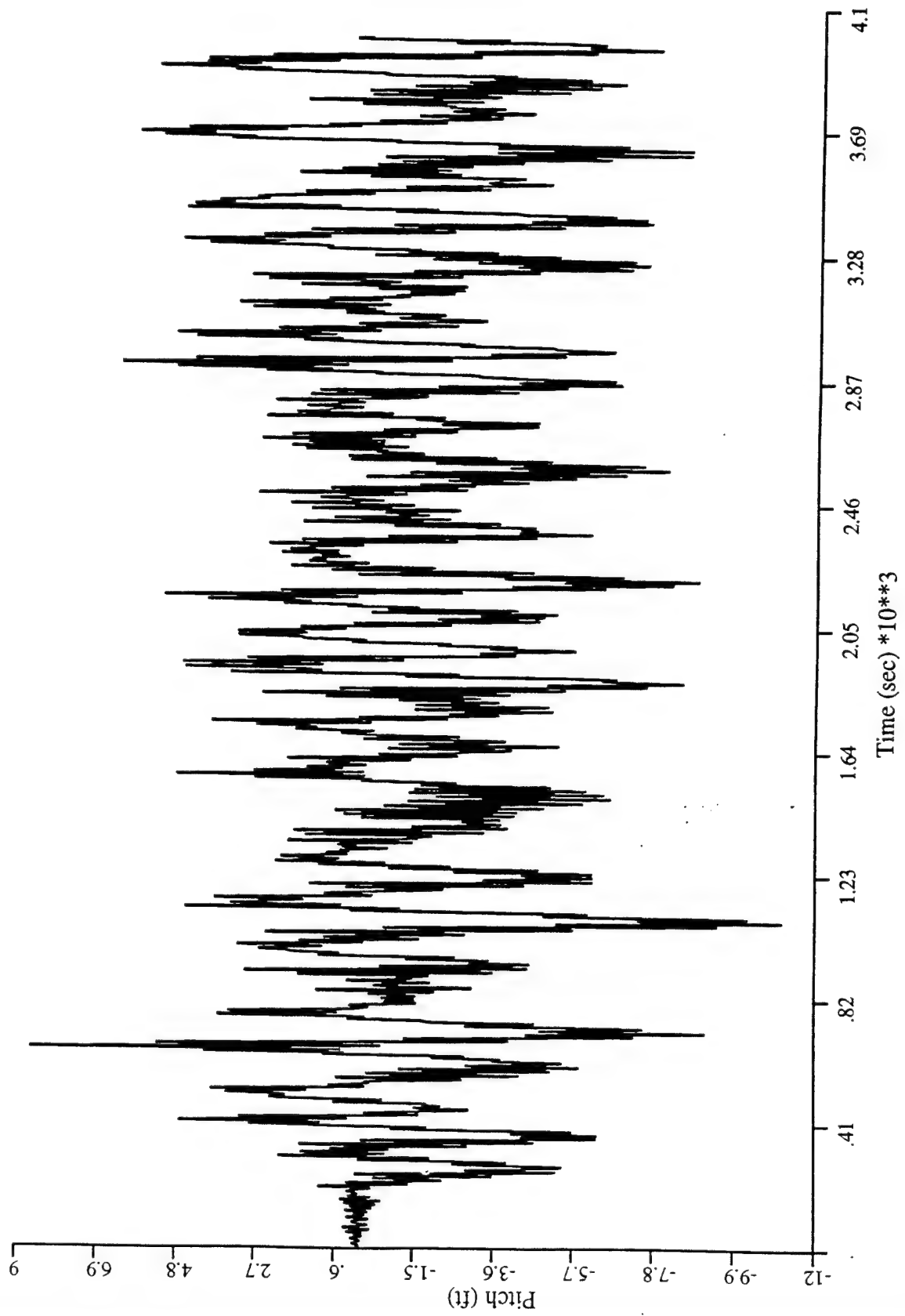


Figure 5.19 Energy spectrum of the simulated pitch motion of the ASOP

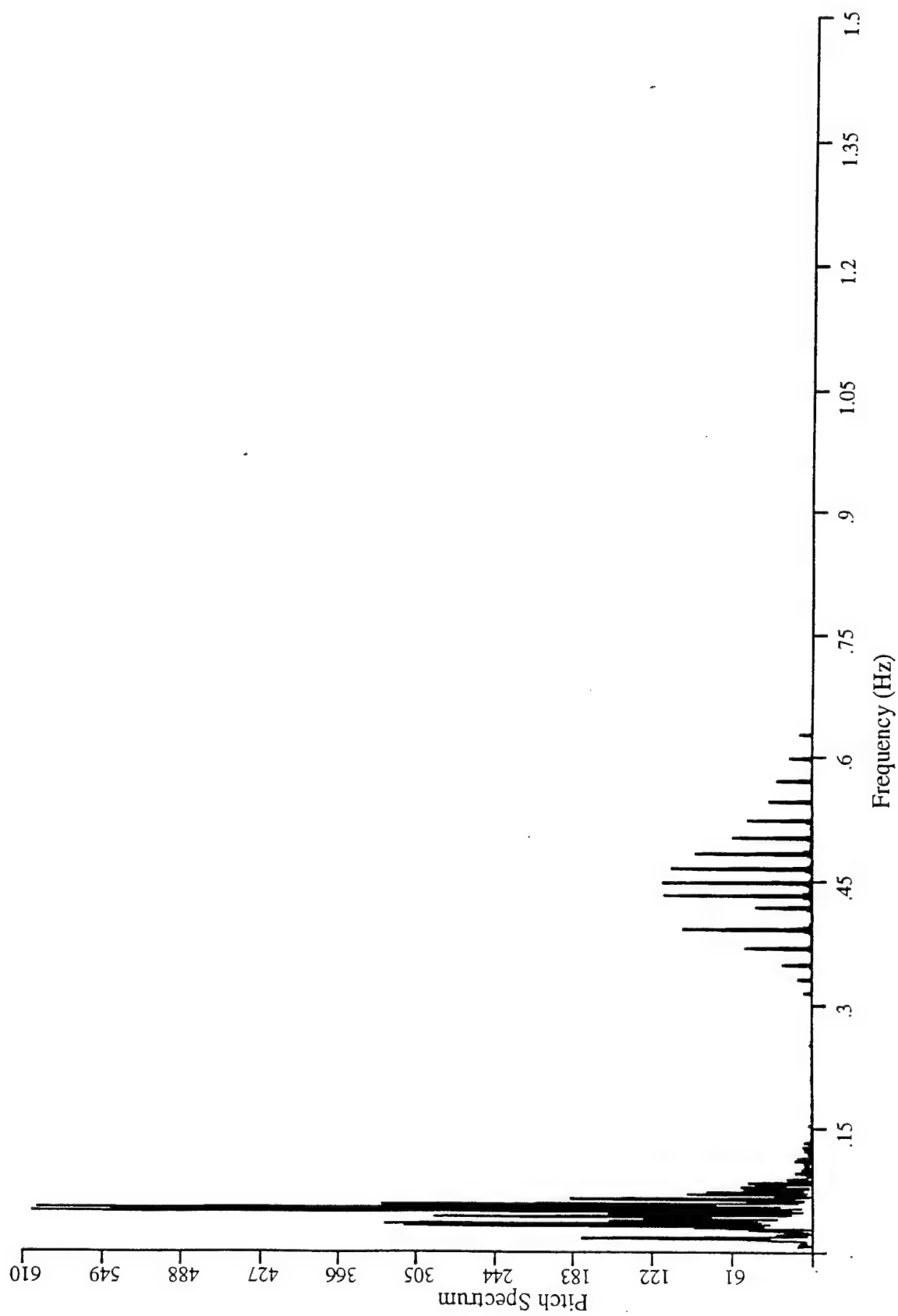


Table 5.1 Statistics of the time domain simulation of the ASOP in 100 year storm

(Hs=39ft, Tp=14.1sec, Gamma=2, JONSWAP)

| | ARTICULATED BUOYS | | FIXED BUOYS | |
|-----------------------------------|-------------------|------------|-------------|------------|
| | SIMULATION | MODEL TEST | SIMULATION | MODEL TEST |
| WAVE ELEVATION: (FT) | | | | |
| MEAN | -0.04 | -0.08 | -0.02 | -0.05 |
| MAX. | 37.10 | 46.64 | 36.53 | 51.07 |
| MIN. | -34.09 | -41.59 | -33.72 | -41.28 |
| RMS | 9.73 | 10.82 | 9.72 | 10.73 |
| SURGE AT CG: (FT) | | | | |
| MEAN | -36.81 | -17.70 | -8.67 | -11.62 |
| MAX. | 6.77 | 29.99 | 7.01 | 25.49 |
| MIN. | -83.99 | -55.86 | -30.86 | -51.31 |
| RMS | 15.93 | 13.90 | 6.48 | 12.57 |
| RMS(L) | 15.45 | 13.57 | 5.16 | 12.16 |
| RMS(H) | 3.97 | 3.04 | 3.91 | 3.18 |
| HEAVE AT CG: (FT) | | | | |
| MEAN | 1.92 | 1.86 | 0.91 | 0.70 |
| MAX. | 14.07 | 22.41 | 11.68 | 26.65 |
| MIN. | -13.65 | -19.52 | -16.03 | -19.29 |
| RMS | 4.49 | 5.91 | 4.40 | 5.96 |
| RMS(L) | 0.96 | 4.58 | 0.58 | 4.59 |
| RMS(H) | 4.38 | 3.73 | 4.36 | 3.80 |
| PITCH: (DEG) | | | | |
| MEAN | -1.27 | -0.51 | -0.15 | -0.17 |
| MAX. | 8.60 | 4.15 | 5.58 | 7.12 |
| MIN. | -11.15 | -8.10 | -4.29 | -6.38 |
| RMS | 2.90 | 1.60 | 1.40 | 1.44 |
| RMS(L) | 2.61 | 1.17 | 0.76 | 0.99 |
| RMS(H) | 1.25 | 1.08 | 1.18 | 1.05 |
| MAX. MOOR TENSION: (KIPS) | | | | |
| MEAN | 726.50 | 465.27 | 331.43 | 346.84 |
| MAX. | 2547.10 | 1424.88 | 529.50 | 1065.92 |
| MIN. | 256.13 | 139.19 | 245.24 | 120.88 |
| RMS | 375.58 | 169.17 | 43.96 | 105.00 |
| VERTICAL FORCE AT JOINT 1: (KIPS) | | | | |
| MEAN | 1728.97 | 1818.33 | | |
| MAX. | 5190.31 | 2820.74 | | |
| MIN. | 213.31 | 494.17 | | |
| RMS | 447.41 | 332.22 | | |
| VERTICAL FORCE AT JOINT 2: (KIPS) | | | | |
| MEAN | 1788.33 | 1819.27 | | |
| MAX. | 3984.30 | 2753.35 | | |
| MIN. | 793.06 | 661.20 | | |
| RMS | 335.60 | 267.60 | | |

Table 5.2 Statistics of the time domain simulation of the ASOP in 10 year storm

(Hs=20ft, Tp=11sec, Gamma=2, JONSWAP)

| | ARTICULATED BUOYS | | FIXED BUOYS | |
|-----------------------------------|-------------------|------------|-------------|------------|
| | SIMULATION | MODEL TEST | SIMULATION | MODEL TEST |
| WAVE ELEVATION: (FT) | | | | |
| MEAN | -0.02 | 0.33 | -0.02 | 0.29 |
| MAX. | 18.48 | 26.65 | 18.25 | 22.86 |
| MIN. | -15.85 | -18.65 | -17.95 | -19.89 |
| RMS | 5.02 | 5.57 | 5.01 | 5.52 |
| SURGE AT CG: (FT) | | | | |
| MEAN | -13.99 | -6.16 | -0.41 | -2.58 |
| MAX. | 3.67 | 15.68 | 3.28 | 15.19 |
| MIN. | -45.73 | -34.96 | -3.55 | -18.52 |
| RMS | 7.75 | 8.37 | 1.08 | 6.18 |
| RMS(L) | 7.68 | 8.32 | 0.44 | 6.12 |
| RMS(H) | 1.02 | 0.84 | 0.98 | 0.82 |
| HEAVE AT CG: (FT) | | | | |
| MEAN | 1.63 | 1.09 | 0.10 | 0.33 |
| MAX. | 5.86 | 13.68 | 3.06 | 10.24 |
| MIN. | -1.68 | -9.26 | -3.52 | -7.22 |
| RMS | 1.15 | 4.04 | 0.97 | 2.82 |
| RMS(L) | 0.62 | 3.93 | 0.05 | 2.63 |
| RMS(H) | 0.97 | 0.96 | 0.97 | 1.02 |
| PITCH: (DEG) | | | | |
| MEAN | -0.35 | -0.06 | 0.00 | -0.11 |
| MAX. | 3.25 | 3.55 | 1.83 | 2.17 |
| MIN. | -6.20 | -3.64 | -1.43 | -2.44 |
| RMS | 1.30 | 1.36 | 0.46 | 0.73 |
| RMS(L) | 1.21 | 1.29 | 0.07 | 0.58 |
| RMS(H) | 0.47 | 0.44 | 0.45 | 0.44 |
| MAX. MOOR TENSION: (KIPS) | | | | |
| MEAN | 374.06 | 354.42 | 282.37 | 300.00 |
| MAX. | 773.71 | 743.58 | 302.96 | 391.93 |
| MIN. | 266.74 | 216.11 | 264.14 | 212.45 |
| RMS | 67.90 | 65.36 | 6.30 | 32.31 |
| VERTICAL FORCE AT JOINT 1: (KIPS) | | | | |
| MEAN | 1705.75 | 1871.24 | | |
| MAX. | 3292.97 | 2626.21 | | |
| MIN. | 893.82 | 1132.22 | | |
| RMS | 249.99 | 255.59 | | |
| VERTICAL FORCE AT JOINT 2: (KIPS) | | | | |
| MEAN | 1705.99 | 1846.19 | | |
| MAX. | 3213.01 | 2472.78 | | |
| MIN. | 1206.54 | 1256.98 | | |
| RMS | 189.78 | 196.26 | | |

CHAPTER 6 MODEL TEST

6.1 General

Model testing was a major part of this conceptual study. The model test program was designed to aid in determining the feasibility of the Articulated Stable Ocean Platform (ASOP) concept, and to reinforce the computational analysis. The main objective of this test was to find the motion characteristics of the ASOP, to determine the effectiveness of the articulation and other types of connections between the hull and buoys to the global motion of the ASOP, and to measure the important hydrodynamic parameters for this concept.

All of the model tests were conducted in the deep water wave and towing basin (300 ft long, 50 ft wide and 15 ft deep) at the Offshore Model Basin (OMB) in Escondido, California. The model had a scale of 1:60. In the model test, different configurations and different type of connections between the hull and buoy were tested in various environmental conditions (regular waves, random waves and currents). The test was organized into two phases. The phase I test was conducted in February 1996, and the phase II test was conducted in April, 1996. The following two sections briefly describe the two phases of the model test and the test results. Detailed information about the model construction, test setup and test results can be found in the model test report from OMB, "Model Studies of Articulated Stable Ocean Platform, Preliminary Report No. OMB-95-214-1".

6.2 Phase I Model Test

In the phase I test, the ASOP with a draft of 130 feet and six cylindrical buoys was tested. Figure 6.1 shows the mooring configuration of the ASOP in the phase I test. This configuration was our original design. After the phase I test, we modified the design and increased the draft to 145 ft in order to reduce the motion. In the test, two types of connections between the buoy and hull (hinged connection and spring connection) were tested. The spring connection was used to further decouple the motion of the buoy from the hull and to reduce interaction forces between the buoys and the hull. Table 6.1 shows the ASOP hydrodynamic configuration. Table 6.4 shows the test matrix of phase I. Table 6.6 shows the

environmental condition used in the test. Among the tests, the buoy damage test was designed to investigate the dynamic behavior of the ASOP during a sudden loss of a buoy and the damage stability. A six point mooring system was used for the station-keeping of the ASOP. The fair-leads of the mooring lines were located at the lower corners of the hexagonal hull. The horizontal stiffness of the mooring system is shown in Figure 6.3, together with the modeled mooring stiffness from the model test. Table 6.2 shows the physical properties of the ASOP in the phase I test. At the end of the phase I test, a series of tests were performed for the ASOP with articulated buoys at 145 ft draft. In this series of test, the platform was simply ballasted to the new draft without changes in other configurations. The objective of the test was to see how sensitive the motion of the platform was to the draft change.

The six degree of freedom natural periods were measured by timing free oscillations of the model in still water. The test results are listed as follows:

| | Universal joint | Spring connection |
|-------|-----------------|-------------------|
| Surge | 188.0 sec | 188.0 sec |
| Heave | 81.0 sec | 92.9 sec |
| Pitch | 61.0 sec | 83.0 sec |

The results of the model test for regular waves are summarized in Table 6.8, and the statistics of the random wave test are listed in Table 6.9. The location of the mooring line #1 and #2, and buoy #1 and #2 are shown in Figure 6.1. The test results shows little difference in the motion of the ASOP between hinged and spring connected buoys, but the heave motion of the ASOP was reduced about 10 percent when the draft was increased to 145 ft. In the random wave tests, strong slow drift motions in surge, heave and pitch were observed. In the 100 year storm wave condition the maximum dynamic tension was six times higher than the mean tension in the mooring line, and the variation of the vertical force at the universal joint was about two times of the pretension.

A large trim angle was observed in the current tests (3.8 degrees in the 4 knots current). Because of the large horizontal spacing among the fair-leads, the asymmetry of the tensions in the mooring lines due to the offset of the ASOP in a current created significant trimming moment and caused the trim.

The buoy damage test showed that the maximum dynamic heeling was about 1.5 larger than the heeling angle at static equilibrium. In the model test, the ASOP did not experience as large a heeling angle as predicted numerically (33 degrees). The numerical analysis was more conservative due to the fact that the contributions of mooring lines to stability was not included in the analysis.

6.3 Phase II Test

In the phase II test, based on the phase I test results that the motion was less at a deeper draft, the draft of ASOP was changed to 145 feet by elongating the center column. The draft of the buoys remained the same as in phase I test. Therefore, the gap between the bottom of the buoys and the hull was increased from 25 to 40 ft. The phase I test also showed that the ASOP experienced large trimming in current due to the moment created by the mooring system. Therefore, in phase II the fair-leads of the mooring line were moved inside to reduce the moment arm. The fair-leads were located on a circle of 60 ft radius at the bottom of the hull. Figure 6.2 shows the general arrangement of the ASOP for the phase II test, and Figure 6.4 shows the target and model test results of the mooring stiffness. In addition to the two types of connection between buoys and hull which were tested in phase I, tests were also performed for the ASOP with buoys which were simply fixed on the hull. The objective was to see the effectiveness of articulation to the motion of the ASOP by comparing with fixed buoys. In phase I, large angular motions of the buoys were observed due to the fact that the natural frequency (pitch and roll) of the buoys was within the wave energy frequency range. To reduce the motion of buoys, a series of buoy tests with water in the buoys' upper compartments were performed. The function of the water in the buoys was: 1) to change the natural frequency of the buoys; and 2) to dissipate energy by creating sloshing in the buoys (damping effects). In the test, seven (7) buoys with different amounts and combinations of water in their upper three compartments were tested in regular and random waves. The configuration which had the best motion overall was chosen to be used in the ASOP tests. Also in phase II, the effects of different buoy shapes on the global motion of the platform were investigated. Four buoy shapes (hourglass shape, inverted cone shape, buoy with link and multi-articulated buoy) were designed in the test. In order to reduce the amount of testing, a buoy test with the four different shaped buoys and the original cylindrical buoys was tested first in regular and random waves. Only the configuration which had the

least vertical force on the universal joint was used in the ASOP test. Figure 6.5 shows the configurations of the buoys with different shapes. Their physical properties can be found in the model test report from OMB. In order to further reduce the wave force and motion of the platform, a series of tests were performed for the ASOP which had no center column and the deck was supported by a frame structure. In this configuration, the diameter of the buoys was increased to 39 ft to keep the same water plane area as the original design. Tables 6.2 and 6.3 show the physical properties of the ASOP with the center column and without the center column in phase II test, respectively. Table 6.5 shows the test matrix and Table 6.7 shows the wave conditions in the phase II test.

In the water damped buoy tests, the motion of the buoys varied with wave frequency and the amount of water in the buoy. In general, the buoys with more water inside had larger motion in long waves, and the buoys with less water inside had larger motion in short waves. The buoy, which was filled with 25 percent of water in each of its upper three compartments had less motion in all the wave conditions and was chosen for the damped buoy configuration test of the ASOP.

In the test of buoys with different shapes, the hourglass shaped buoy had the least vertical force at the universal joint in all wave conditions, and was chosen for the optimized buoy configuration test of the ASOP.

The surge, heave and pitch natural periods of the ASOP and the natural period (pitch) of the buoys were measured by timing free oscillations of the model in still water. The test results for fixed, universal joint and spring connections are listed as follows:

| | Fixed | Universal joint | Spring connection |
|------------|--------|-----------------|-------------------|
| Surge | -- | 212.0 sec | 215.0 sec |
| Heave | -- | 81.0 sec | 96.0 sec |
| Pitch | 67 sec | 70.0 sec | 116.0 sec |
| Buoy Pitch | -- | 14.0 sec | 15.7 sec |

For the universal joint configuration, the natural periods obtained numerically in Chapter 5 were 214.2, 88.0, 68.2 and 14.1 seconds in surge, heave, pitch and buoy pitch, respectively, and they agreed well with the model tests.

The test results of the ASOP in regular and random waves in phase II are summarized in Tables 6.10 to 6.16. Figures 6.6 to 6.8 show the response amplitude operator of the ASOP obtained from the regular wave tests. The results show that the configuration which had best motion is wave frequency dependent, and there was no one particular configuration which was absolutely better in motion than the rest. Allowing the buoys to move by means of articulation did not have a clear advantage over the fixed buoys. The reason is explained in Chapter 5. In random waves, the wave frequency motions of the ASOP was similar among all the configurations, but the ASOP with fixed buoys showed less slow drift motion than the rest. As explained in Chapter 5, this phenomenon may have been caused by the fact that the large angle rotational motion of the buoys introduced more nonlinear forces into the system and, in turn, created larger drift motions.

In the current test, VIV (vortex induced vibration) was observed when the current speed was over 3 knot. The trimming was greatly reduced due to the change of mooring configuration. In a 4 knot current, the trimming is 1.25 degrees. In the phase I test, the same speed current caused a trim angle of 3.8 degrees.

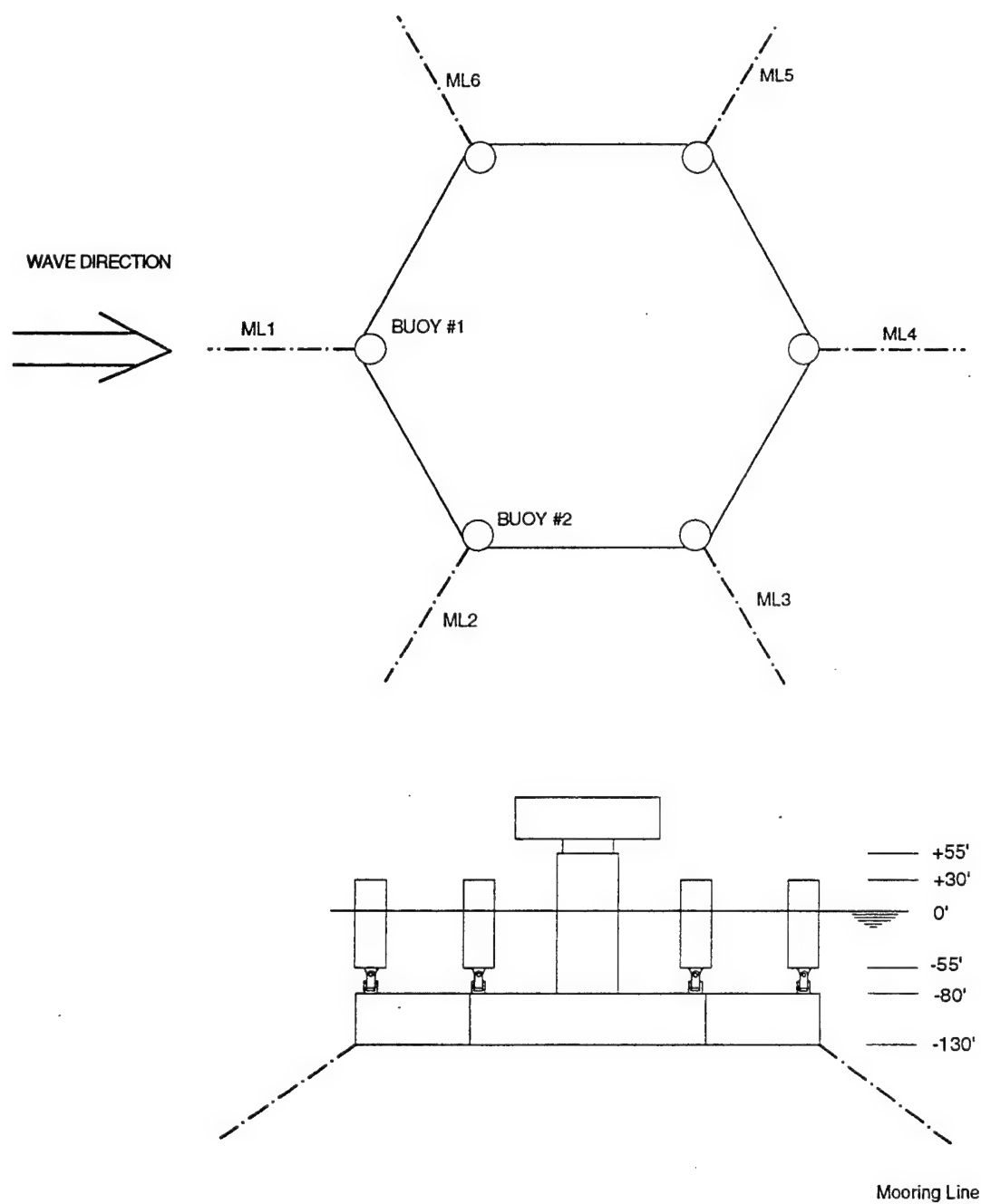


Figure 6.1 The ASOP and mooring configurations in phase I test.

Figure 6.3 Static offset test (surge) in phase I test.

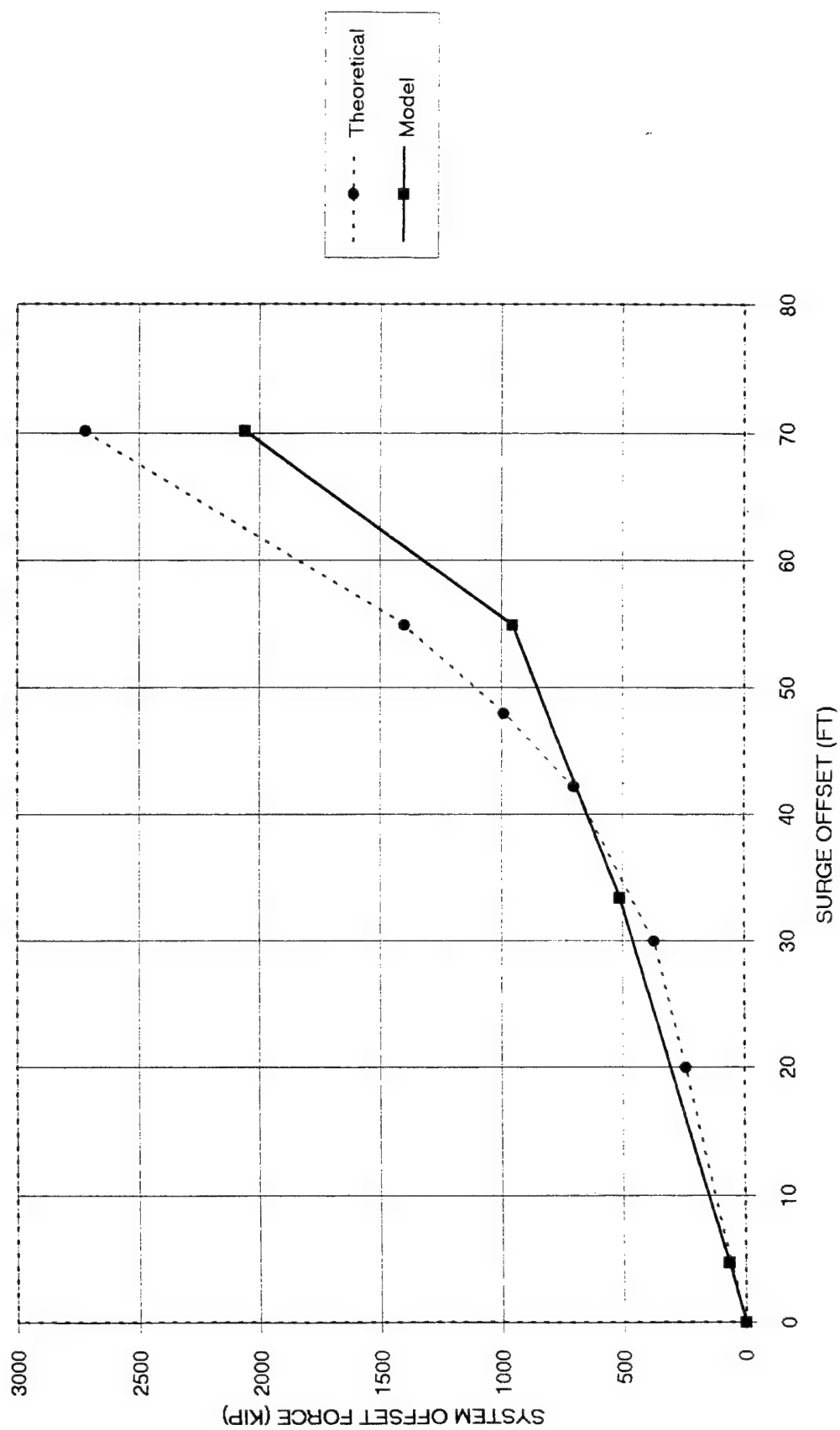
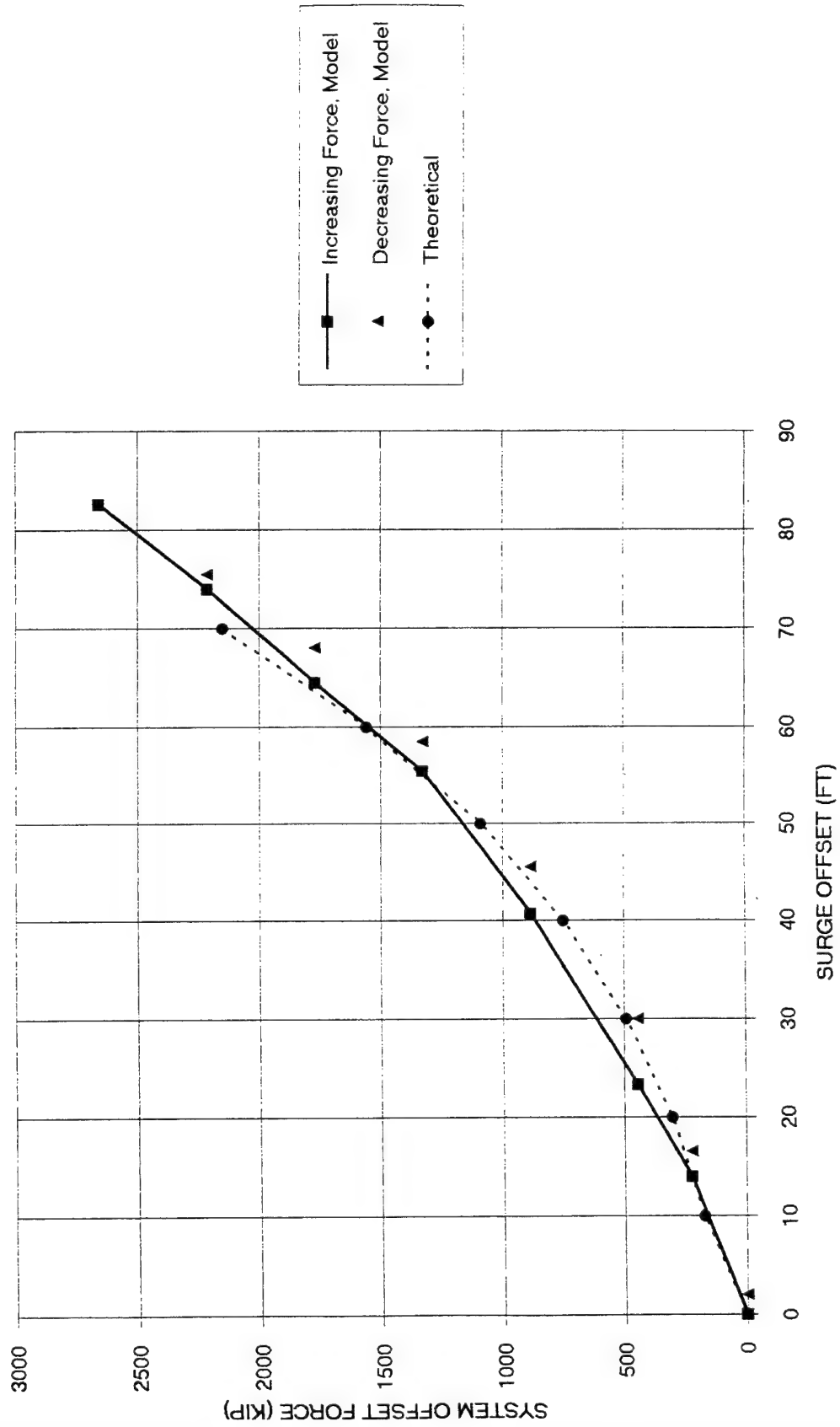


Figure 6.4 Static offset test (surge) in phase II test.



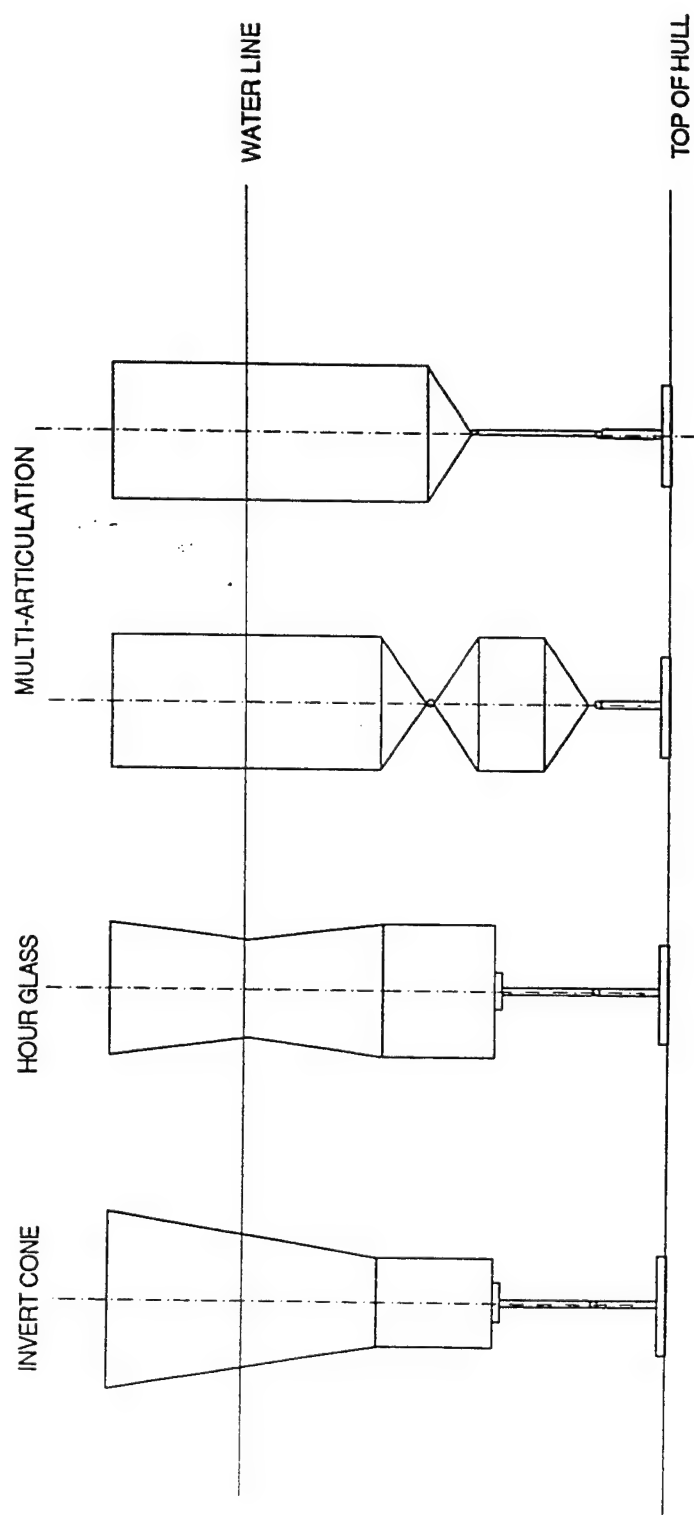


Figure 6.5 Buoy configurations in the buoy test in phase II

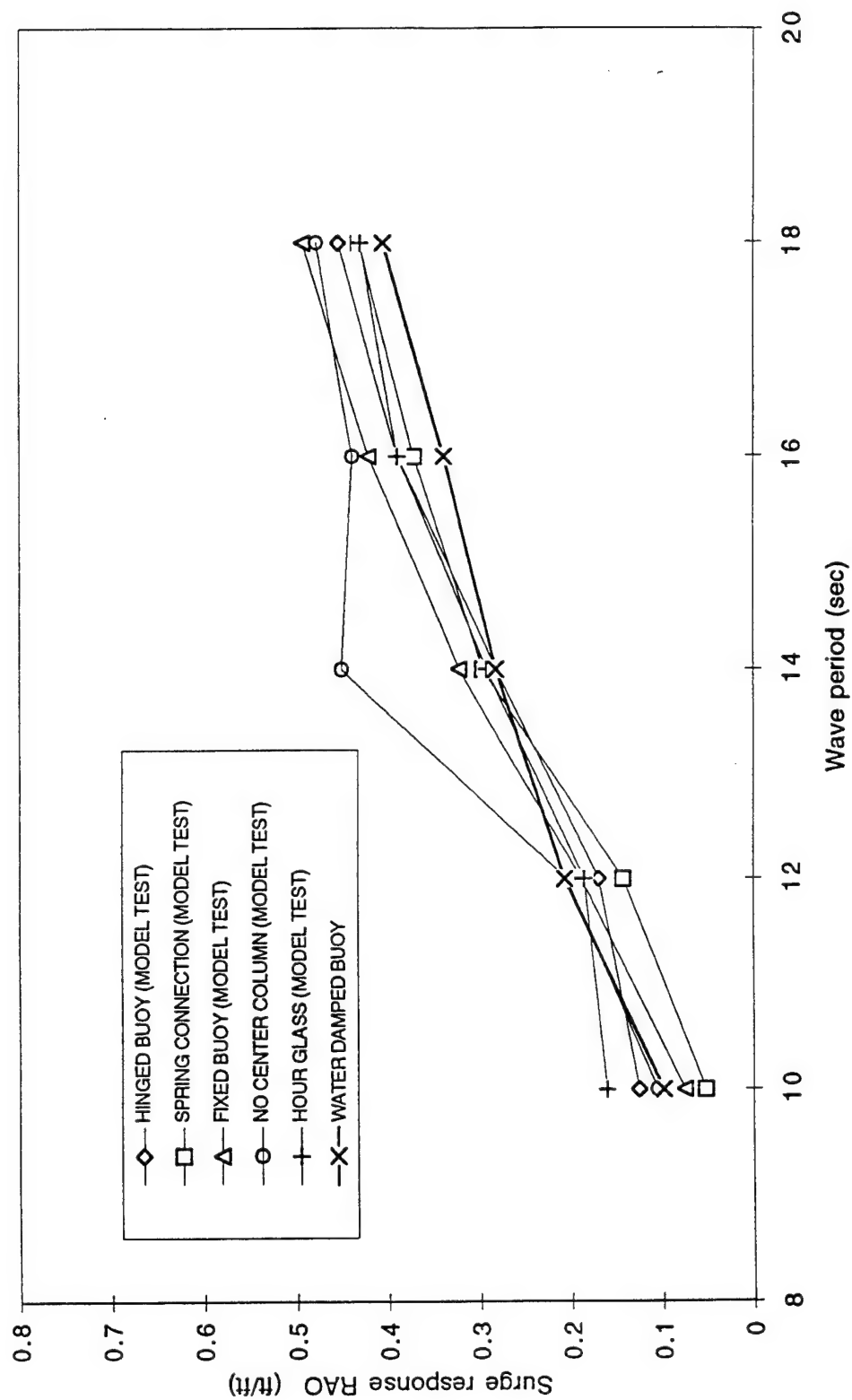


Figure 6.6 Surge response RAO from the regular wave tests.

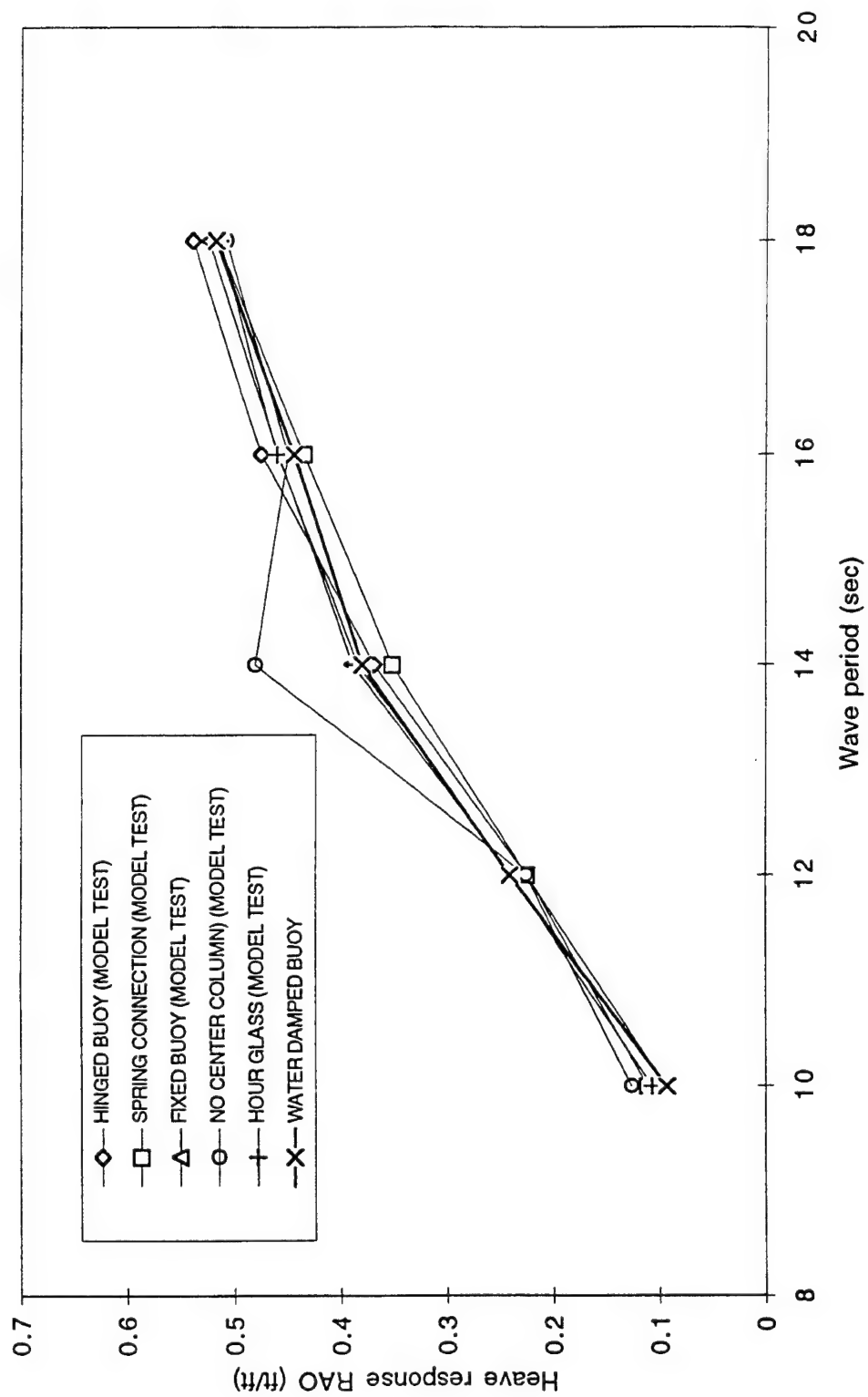


Figure 6.7 Heave response RAO from the regular wave tests.

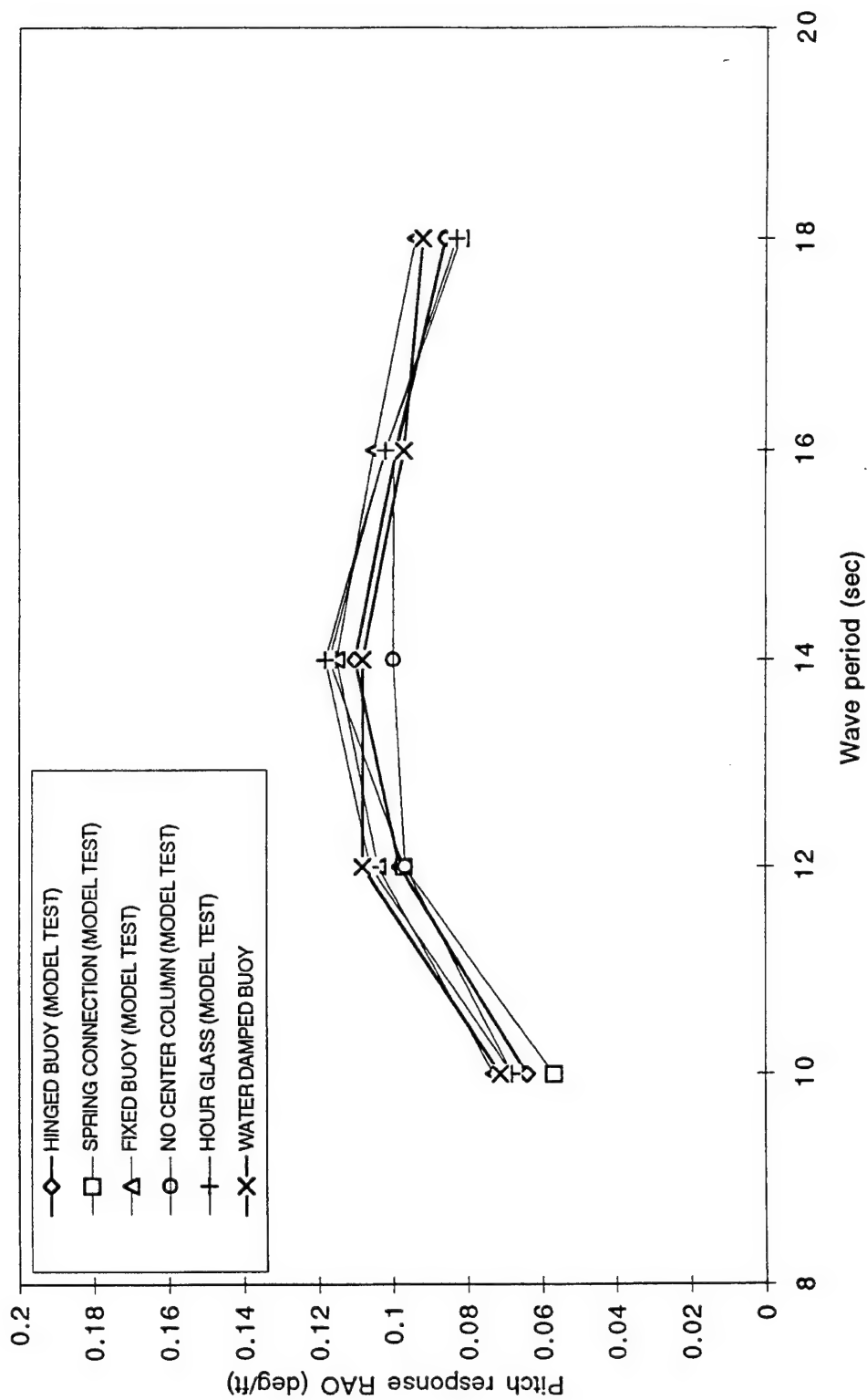


Figure 6.8 Pitch response RAO from the regular wave tests.

Table 6.1 The ASOP configuration in phase I test.

| | |
|---------------------------------|--------------|
| Hull: | |
| Draft | 130 ft |
| Hull diameter(across corner) | 450 ft |
| Hull height | 50 ft |
| Center Column diameter | 60 ft |
| Center column height | 135 ft |
| Total displacement (with buoys) | 450,287 kips |
| KG | 32.41 ft |
| KB | 27.2 ft |
| Radius of gyration Rxx | 107.58 ft |
| Radius of gyration Ryy | 107.58 ft |
| Radius of gyration Rzz | 142 ft |
| Buoys: | |
| Buoy diameter | 30 ft |
| Buoy length | 85 ft |
| Buoy draft | 55 ft |
| Buoy weight | 850 kips |
| KG | 42.5 ft |
| Radius of gyration Rxx, Ryy | 25.66 ft |

Table 6.2 The ASOP configuration in phase II test.

| | |
|---------------------------------|-------------|
| Hull: | |
| Draft | 145 ft |
| Hull diameter(across corner) | 450 ft |
| Hull height | 50 ft |
| Center Column diameter | 60 ft |
| Center column height | 150 ft |
| Total displacement (with buoys) | 452865 kips |
| KG | 33.3 ft |
| KB | 27.8 ft |
| Radius of gyration Rxx | 108.5 ft |
| Radius of gyration Ryy | 108.5 ft |
| Radius of gyration Rzz | 141.8 ft |
| Buoy: | |
| Buoy diameter | 30 ft |
| Buoy length | 85 ft |
| Buoy draft | 55 ft |
| Buoy weight | 850 kips |
| KG | 42.5 ft |
| Radius of gyration Rxx, Ryy | 25.66 ft |

Table 6.3 The ASOP (without center column) configuration in phase II test.

| | |
|---------------------------------|-------------|
| Hull: | |
| Draft | 145 ft |
| Hull diameter(across corner) | 450 ft |
| Hull height | 50 ft |
| Total displacement (with buoys) | 435810 kips |
| KG | 33.2 ft |
| KB | 25 ft |
| Radius of gyration Rxx | 108.5 ft |
| Radius of gyration Ryy | 108.5 ft |
| Radius of gyration Rzz | 141.8 ft |
| Buoy: | |
| Buoy diameter | 39 ft |
| Buoy length | 85 ft |
| Buoy draft | 55 ft |
| Buoy weight | 1400 kips |
| KG | 42.5 ft |
| Radius of gyration Rxx, Ryy | 27.66 ft |

Table 6.4 Test matrix of the phase I test.

| Test no. | Type of test | 130 ft draft | | | 145 ft draft | Notes |
|----------|------------------|--------------|---------------------|---------------------|--------------|----------------|
| | | U joint | Spiing ¹ | Spring ² | U joint | |
| 1 | Static offset | x | | | | Calm water |
| 2 | Surge free decay | x | | | | Calm water |
| 3 | Sway free decay | x | | | | Calm water |
| 4 | Heave free decay | x | | | | Calm water |
| 5 | Roll free decay | x | | | | Calm water |
| 6 | Pitch free decay | x | | | | Calm water |
| 7 | Yaw free decay | x | | | | Calm water |
| 8 | Regular wave 1 | x | x | x | x | |
| 9 | Regular wave 2 | x | x | x | x | |
| 10 | Regular wave 3 | x | x | x | x | |
| 11 | Irregular wave 1 | x | x | x | x | |
| 12 | Irregular wave 2 | x | x | x | x | |
| 13 | Irregular wave 3 | x | x | x | x | |
| 14 | Current only | x | | | | 4 speed towing |
| 15 | Buoy damage test | x | | | | Calm water |

1. Spring stiffness 30 kips/ft.
2. Spring stiffness 45 kips/ft.

Table 6.5 Test matrix of the phase II test.

| No. | Type of test | Buoy test | | ASOP with center column | | | | | ASOP without center column | |
|-----|------------------|----------------|-----------------|-------------------------|-------|--------|--------|-----------|----------------------------|-------|
| | | I ¹ | II ² | U joint | Fixed | Spring | Damped | Optimized | U joint | Fixed |
| 1 | Static offset | | | x | | | | | | |
| 2 | Surge free decay | | | x | x | x | x | x | x | x |
| 3 | Sway free decay | | | x | x | x | x | x | x | x |
| 4 | Heave free decay | | | x | x | x | x | x | x | x |
| 5 | Roll free decay | | | x | x | x | x | x | x | x |
| 6 | Pitch free decay | | | x | x | x | x | x | x | x |
| 7 | Yaw free decay | | | x | x | x | x | x | x | x |
| 8 | Regular wave 1 | x | x | x | x | x | x | x | x | x |
| 9 | Regular wave 2 | x | x | x | x | x | x | x | x | x |
| 10 | Regular wave 3 | x | x | x | x | x | x | x | x | x |
| 11 | Regular wave 4 | x | x | x | x | x | x | x | x | x |
| 12 | Regular wave 5 | x | x | x | x | x | x | x | x | x |
| 13 | Irregular wave 1 | x | x | x | x | x | x | x | x | x |
| 14 | Irregular wave 2 | x | x | x | x | x | x | x | x | x |
| 15 | Current only | | | x | | | | | | |

1. A series of buoy tests with different mount of water in the buoys' upper compartments.
2. A series of buoy tests with different buoy shapes (inverted cone, hour glass, multi-articulation, etc.)

Table 6.6 Wave conditions in phase I test.

| Wave | Wave height | Wave period | Spectrum | Note |
|------------------|-------------|-------------|----------|---------------|
| Regular wave 1 | 12 ft | 8.0 sec | | |
| Regular wave 2 | 20 ft | 12.9 sec | | |
| Regular wave 3 | 20 ft | 20.0 sec | | |
| Irregular wave 1 | 39 ft | 14.1 sec | JONSWAP | 100 yr. storm |
| Irregular wave 2 | 20 ft | 11.0 sec | JONSWAP | 10 yr. storm |
| Irregular wave 3 | 9 ft | 8.5 sec | PM | 95% non-ex. |

Table 6.7 Wave conditions in phase II test.

| Wave | Wave height | Wave period | Spectrum | Note |
|------------------|-------------|-------------|----------|---------------|
| Regular wave 1 | 12 ft | 10.0 sec | | |
| Regular wave 2 | 12 ft | 12.0 sec | | |
| Regular wave 3 | 20 ft | 14.0 sec | | |
| Regular wave 4 | 20 ft | 16.0 sec | | |
| Regular wave 5 | 20 ft | 18.0 sec | | |
| Irregular wave 1 | 39 ft | 14.1 sec | JONSWAP | 100 yr. storm |
| Irregular wave 2 | 20 ft | 11.0 sec | JONSWAP | 10 yr. storm |

Table 6.8 Summary of the regular wave test results in phase I.

| | Hinged buoys, 130 ft draft | | | Hinged buoys, 145 ft draft | | | Spring buoy connection, 130 ft draft (spring stiffness = 45kips/ft) | | |
|--|----------------------------|-----------|-----------|----------------------------|-----------|-----------|--|-----------|-----------|
| Wave condition: | Regular 1 | Regular 2 | Regular 3 | Regular 1 | Regular 2 | Regular 3 | Regular 1 | Regular 2 | Regular 3 |
| Wave Directions deg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wave Ampl. | 6.0 | 10.0 | 10.0 | 6.0 | 10.0 | 10.0 | 6.0 | 10.0 | 10.0 |
| Period | 8.0 | 12.9 | 20.0 | 8.0 | 12.9 | 20.0 | 8.0 | 12.9 | 20.0 |
| Response: (CG) | | | | | | | | | |
| Surge (ft) Amp. | 0.269 | 2.770 | 6.463 | 0.297 | 2.800 | 6.732 | 0.382 | 3.012 | 6.746 |
| Heave (ft) Amp. | 0.269 | 2.970 | 6.449 | 0.127 | 2.574 | 6.067 | 0.127 | 2.956 | 6.435 |
| Pitch (deg) Amp. | 0.113 | 1.372 | 0.976 | 0.009 | 1.202 | 0.976 | 0.113 | 1.372 | 1.004 |
| Mooring Tension (kips) | | | | | | | | | |
| Line 1 Amp. | 4.766 | 11.143 | 40.000 | 3.649 | 7.877 | 38.792 | 3.578 | 10.069 | 37.320 |
| Line 2 Amp. | 2.136 | 9.350 | 25.993 | 1.768 | 7.539 | 23.858 | 1.768 | 9.475 | 27.379 |
| Vertical force on U Joint: (kips) | | | | | | | | | |
| Buoy 1 Amp. | 90.326 | 134.250 | 51.393 | 70.484 | 132.102 | 52.722 | | | |
| Buoy 2 Amp. | 43.690 | 85.714 | 72.700 | 37.646 | 87.469 | 69.862 | | | |

Table 6.9 Statistics of the random wave test results in phase I.

| | | Hinged buoys, 130 ft draft | | | Hinged buoys, 145 ft draft | | | Spring connection, 130 ft draft (spring stiffness = 45kips/ft) | | |
|-----------------------------------|-----------|----------------------------|-------------|-------------|----------------------------|-------------|-------------|---|-------------|-------------|
| Wave condition: | | 100 yr storm | 10 yr storm | 95% non-ex. | 100 yr storm | 10 yr storm | 95% non-ex. | 100 yr storm | 10 yr storm | 95% non-ex. |
| Wave (Jonswap) | Hs (ft) | 39.0 | 20.0 | 9.0 | 39.0 | 20.0 | 9.0 | 39.0 | 20.0 | 9.0 |
| | Tp (sec) | 14.1 | 11.0 | 8.5 | 14.1 | 11.0 | 8.5 | 14.1 | 11.0 | 8.5 |
| | Gamma | 2.0 | 2.0 | 1.0 | 2.0 | 2.0 | 1.0 | 2.0 | 2.0 | 1.0 |
| Wave: (ft) (measured) | mean | 0.323 | 0.437 | 0.405 | 0.345 | 0.422 | 0.314 | 0.395 | 0.449 | |
| | rms | 12.078 | 5.700 | 2.438 | 12.139 | 5.716 | 2.524 | 12.509 | 5.695 | |
| | max | 49.449 | 26.050 | 9.578 | 49.306 | 23.964 | 9.602 | 50.678 | 28.882 | |
| | min | -47.744 | -16.879 | -9.149 | -45.531 | -16.939 | -9.453 | -44.324 | -17.934 | |
| Response: (CG) | | | | | | | | | | |
| Surge (ft) | mean | -20.758 | -6.155 | -0.698 | -17.689 | -10.024 | -1.856 | -17.515 | -6.030 | |
| | rms | 15.770 | 7.926 | 1.448 | 14.350 | 9.282 | 3.630 | 15.980 | 6.110 | |
| | rms (low) | 15.310 | 7.900 | 1.420 | 13.900 | 9.220 | 3.620 | 15.530 | 6.040 | |
| | rms(high) | 3.760 | 0.970 | 0.310 | 3.570 | 1.070 | 0.300 | 3.740 | 0.920 | |
| | max | 22.385 | 16.430 | 3.606 | 24.284 | 14.501 | 5.951 | 26.007 | 14.501 | |
| | min | -66.522 | -27.695 | -5.151 | -58.577 | -37.686 | -9.404 | -78.451 | -37.686 | |
| Heave (ft) | mean | 2.387 | 1.348 | 0.321 | 1.023 | 0.670 | 0.223 | 3.452 | 1.570 | |
| | rms | 6.230 | 3.986 | 1.419 | 4.970 | 2.556 | 1.020 | 5.910 | 3.600 | |
| | rms (low) | 4.940 | 3.790 | 1.410 | 3.530 | 2.430 | 1.000 | 4.470 | 3.480 | |
| | rms(high) | 3.800 | 0.900 | 0.230 | 3.490 | 0.800 | 0.210 | 3.880 | 0.930 | |
| | max | 30.631 | 14.645 | 4.072 | 21.683 | 9.690 | 3.349 | 33.758 | 9.690 | |
| | min | -14.328 | -9.715 | -3.741 | -18.358 | -6.250 | -2.477 | -12.428 | -6.250 | |
| Pitch (deg) | mean | -0.035 | -0.037 | -0.027 | -0.038 | 0.059 | 0.005 | -1.458 | -0.140 | |
| | rms | 1.940 | 1.190 | 0.419 | 1.690 | 0.888 | 0.360 | 2.400 | 1.260 | |
| | rms (low) | 1.400 | 1.050 | 0.400 | 1.210 | 0.780 | 0.340 | 1.990 | 1.140 | |
| | rms(high) | 1.340 | 0.520 | 0.140 | 1.170 | 0.430 | 0.100 | 1.340 | 0.540 | |
| | max | 5.847 | 3.811 | 1.184 | 5.355 | 2.870 | 1.210 | 4.123 | 2.870 | |
| | min | -8.890 | -4.174 | -1.288 | -7.939 | -2.961 | -1.288 | -11.546 | -2.961 | |
| Mooring Tension: (kips) | | | | | | | | | | |
| Line 1 | mean | 300.967 | 215.167 | 175.420 | 406.641 | 333.037 | 271.975 | 506.058 | 338.260 | |
| | rms | 125.690 | 52.500 | 13.778 | 134.550 | 60.606 | 22.980 | 205.780 | 41.400 | |
| | rms (low) | 120.470 | 52.170 | 13.450 | 126.370 | 60.240 | 22.830 | 193.450 | 40.940 | |
| | rms(high) | 35.830 | 5.950 | 2.670 | 46.200 | 6.320 | 2.630 | 70.150 | 6.190 | |
| | max | 1665.293 | 370.234 | 224.914 | 1798.618 | 524.930 | 332.594 | 2818.098 | 524.930 | |
| | min | 32.579 | 92.417 | 143.706 | 144.533 | 183.000 | 221.467 | 266.447 | 183.000 | |
| Line 2 | mean | 310.146 | 257.650 | 235.632 | 332.705 | 302.214 | 277.265 | 270.428 | 227.350 | |
| | rms | 60.480 | 27.460 | 7.105 | 45.550 | 27.976 | 10.700 | 83.080 | 23.010 | |
| | rms (low) | 57.540 | 27.260 | 6.990 | 43.420 | 27.780 | 10.600 | 76.270 | 22.730 | |
| | rms(high) | 18.650 | 3.360 | 1.480 | 13.770 | 3.270 | 1.460 | 32.940 | 3.610 | |
| | max | 876.646 | 330.599 | 256.307 | 593.327 | 385.310 | 303.588 | 1270.393 | 385.310 | |
| | min | 159.728 | 189.445 | 215.447 | 210.723 | 233.011 | 251.584 | 118.867 | 233.011 | |
| Vertical force on U joint: (kips) | | | | | | | | | | |
| Buoy 1 | mean | 8.829 | 16.231 | -0.264 | -20.234 | 13.187 | 3.981 | | | |
| | rms | 315.340 | 208.790 | 91.718 | 264.640 | 165.491 | 72.520 | | | |
| | rms (low) | 286.620 | 191.430 | 85.510 | 238.380 | 151.860 | 67.280 | | | |
| | rms(high) | 131.490 | 83.360 | 34.870 | 114.940 | 66.120 | 27.060 | | | |
| | max | 935.658 | 708.081 | 276.372 | 799.476 | 484.922 | 196.950 | | | |
| | min | -1439.129 | -823.372 | 292.749 | -1285.576 | -627.451 | -206.608 | | | |
| Buoy 2 | mean | -44.616 | 553.462 | 41.329 | -31.554 | -3.826 | 0.133 | | | |
| | rms | 230.440 | 311.700 | 113.762 | 186.370 | 118.481 | 49.499 | | | |
| | rms (low) | 209.830 | 305.270 | 114.820 | 165.240 | 109.330 | 46.760 | | | |
| | rms(high) | 95.270 | 63.010 | 110.890 | 86.190 | 45.920 | 18.210 | | | |
| | max | 595.225 | 987.807 | 840.535 | 500.475 | 331.355 | 155.724 | | | |
| | min | -971.621 | -407.828 | -202.300 | -864.030 | -415.750 | -124.441 | | | |

Table 6.10 Statistics of the test results in regular wave (wave height=15ft, period=10sec)

| REGULAR WAVE: H=15 FT, T=10 SEC | | | | | | | |
|---------------------------------|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.32 | 0.27 | 0.18 | 0.40 | 0.17 | 0.11 |
| | MAX | 8.05 | 8.11 | 8.28 | 8.46 | 7.68 | 8.42 |
| | MIN | -7.45 | -8.96 | -8.49 | -8.32 | -9.21 | -9.75 |
| | RMS | 5.13 | 5.46 | 5.50 | 5.43 | 5.57 | 4.97 |
| SURGE: (FT) | | | | | | | |
| | MEAN | 9.81 | -3.62 | 0.68 | -15.71 | -6.96 | -6.04 |
| | MAX | 24.00 | 5.64 | 5.06 | 5.43 | -2.11 | 22.27 |
| | MIN | -3.98 | -12.22 | -2.72 | -37.90 | -11.51 | -31.52 |
| | RMS | 9.30 | 5.66 | 1.74 | 12.34 | 2.89 | 16.59 |
| | RMS(L) | 9.27 | 5.65 | 1.65 | 12.30 | 2.88 | 16.58 |
| | RMS(H) | 0.64 | 0.41 | 0.54 | 0.87 | 0.29 | 0.52 |
| | RAO | 0.125 | 0.075 | 0.098 | 0.160 | 0.052 | |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 1.74 | 0.71 | 0.76 | 1.75 | 0.81 | 1.19 |
| | MAX | 4.55 | 2.59 | 3.16 | 4.56 | 2.99 | 4.75 |
| | MIN | -1.01 | -1.13 | -1.89 | -0.57 | -1.27 | -1.06 |
| | RMS | 1.14 | 0.85 | 1.00 | 1.13 | 0.88 | 1.18 |
| | RMS(L) | 1.04 | 0.68 | 0.85 | 0.97 | 0.62 | 1.00 |
| | RMS(H) | 0.48 | 0.52 | 0.51 | 0.58 | 0.62 | 0.63 |
| | RAO | 0.094 | 0.095 | 0.093 | 0.107 | 0.111 | |
| PITCH: DEG) | | | | | | | |
| | MEAN | -0.05 | 0.06 | -0.02 | 0.01 | -0.34 | -0.02 |
| | MAX | 1.24 | 0.94 | 1.03 | 1.15 | 0.40 | 2.50 |
| | MIN | -1.42 | -0.71 | -0.82 | -1.50 | -1.10 | -2.72 |
| | RMS | 0.61 | 0.42 | 0.42 | 0.48 | 0.34 | 0.91 |
| | RMS(L) | 0.51 | 0.13 | 0.15 | 0.30 | 0.11 | 0.84 |
| | RMS(H) | 0.33 | 0.40 | 0.39 | 0.37 | 0.32 | 0.34 |
| | RAO | 0.064 | 0.073 | 0.071 | 0.068 | 0.057 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1879.24 | | 1477.93 | 1685.82 | 1666.76 | |
| | MAX | 2194.35 | | 1708.03 | 1883.11 | 1805.30 | |
| | MIN | 1521.03 | | 1221.71 | 1470.70 | 1560.19 | |
| | RMS | 114.58 | | 116.81 | 62.52 | 60.36 | |
| | RMS(L) | 98.61 | | 41.39 | 42.63 | 14.37 | |
| | RMS(H) | 105.73 | | 109.24 | 45.74 | 85.63 | |
| | RAO | 20.610 | 0.000 | 19.862 | 8.424 | 15.373 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1837.60 | | 1425.06 | 1583.82 | 1671.63 | |
| | MAX | 2070.98 | | 1606.83 | 1710.74 | 1780.02 | |
| | MIN | 1596.43 | | 1229.27 | 1444.03 | 1596.43 | |
| | RMS | 104.95 | | 91.85 | 45.06 | 43.98 | |
| | RMS(L) | 72.78 | | 38.86 | 39.49 | 12.83 | |
| | RMS(H) | 75.61 | | 83.23 | 21.71 | 42.06 | |
| | RAO | 14.739 | 0.000 | 15.133 | 3.998 | 7.551 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 325.81 | 282.53 | 317.87 | 313.98 | 291.53 | 288.74 |
| | MAX | 413.91 | 329.67 | 340.65 | 498.16 | 322.34 | 472.52 |
| | MIN | 241.75 | 234.43 | 285.71 | 201.46 | 260.07 | 146.52 |
| | RMS | 53.72 | 27.33 | 11.65 | 75.00 | 16.64 | 89.73 |
| | RMS(L) | 53.53 | 27.12 | 11.02 | 74.68 | 16.30 | 89.61 |
| | RMS(H) | 4.54 | 3.44 | 3.77 | 6.90 | 3.36 | 4.50 |
| | RAO | 0.885 | 0.630 | 0.685 | 1.271 | 0.603 | |

Table 6.11 Statistics of the test results in regular wave (wave height=15ft, period=12sec)

| REGULAR WAVE: H=15 FT, T=12 SEC | | | | | | | |
|---------------------------------|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.26 | 0.17 | 0.15 | 0.07 | 0.01 | 0.20 |
| | MAX. | 8.35 | 8.54 | 7.92 | 7.52 | 7.98 | 8.09 |
| | MIN. | -9.57 | -8.66 | -9.03 | -8.77 | -10.12 | -8.92 |
| | RMS | 5.63 | 5.84 | 5.73 | 5.45 | 5.78 | 5.48 |
| SURGE: (FT) | | | | | | | |
| | MEAN | -7.36 | -7.16 | 0.85 | 5.83 | -1.34 | -4.03 |
| | MAX. | -0.98 | 3.08 | 4.08 | 19.02 | 1.86 | 8.07 |
| | MIN. | -14.69 | -17.12 | -5.36 | -8.06 | -6.02 | -17.99 |
| | RMS | 3.17 | 5.81 | 1.94 | 6.67 | 1.64 | 7.16 |
| | RMS(L) | 3.03 | 5.71 | 1.54 | 6.68 | 1.42 | 7.07 |
| | RMS(H) | 0.95 | 1.10 | 1.18 | 1.01 | 0.82 | 1.12 |
| | RAO | 0.169 | 0.188 | 0.206 | 0.185 | 0.142 | |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 1.24 | 0.52 | 1.01 | 1.11 | 0.58 | 2.01 |
| | MAX. | 4.70 | 3.32 | 4.28 | 4.59 | 3.77 | 5.55 |
| | MIN. | -2.17 | -2.27 | -2.30 | -2.12 | -1.90 | -0.78 |
| | RMS | 1.51 | 1.45 | 1.50 | 1.56 | 1.41 | 1.50 |
| | RMS(L) | 0.82 | 0.38 | 0.59 | 0.84 | 0.55 | 0.85 |
| | RMS(H) | 1.27 | 1.40 | 1.38 | 1.31 | 1.30 | 1.24 |
| | RAO | 0.226 | 0.240 | 0.241 | 0.240 | 0.225 | |
| PITCH: DEG | | | | | | | |
| | MEAN | -0.08 | 0.01 | 0.26 | -0.20 | -0.14 | -0.10 |
| | MAX. | 1.32 | 1.08 | 1.76 | 1.33 | 1.06 | 1.03 |
| | MIN. | -1.42 | -1.07 | -1.10 | -1.78 | -1.48 | -1.22 |
| | RMS | 0.59 | 0.62 | 0.67 | 0.69 | 0.58 | 0.53 |
| | RMS(L) | 0.23 | 0.07 | 0.25 | 0.37 | 0.17 | 0.08 |
| | RMS(H) | 0.55 | 0.61 | 0.62 | 0.58 | 0.56 | 0.53 |
| | RAO | 0.098 | 0.104 | 0.108 | 0.106 | 0.097 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1897.77 | | 1520.97 | 1687.64 | 1637.01 | |
| | MAX. | 2120.43 | | 1723.59 | 1871.44 | 1801.40 | |
| | MIN. | 1630.22 | | 1252.83 | 1517.39 | 1536.84 | |
| | RMS | 109.92 | | 116.03 | 64.08 | 60.45 | |
| | RMS(L) | 30.52 | | 38.35 | 44.08 | 16.75 | |
| | RMS(H) | 105.60 | | 109.51 | 46.52 | 58.09 | |
| | RAO | 18.757 | 0.000 | 19.112 | 8.536 | 10.050 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1861.13 | | 1456.70 | 1601.04 | 1646.79 | |
| | MAX. | 2050.19 | | 1641.46 | 1741.92 | 1780.02 | |
| | MIN. | 1665.71 | | 1246.59 | 1475.20 | 1558.33 | |
| | RMS | 91.74 | | 88.70 | 50.60 | 48.18 | |
| | RMS(L) | 29.51 | | 29.41 | 34.41 | 11.67 | |
| | RMS(H) | 86.86 | | 83.68 | 37.10 | 46.74 | |
| | RAO | 15.428 | 0.000 | 14.604 | 6.807 | 8.087 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 342.84 | 278.56 | 314.48 | 311.42 | 294.50 | 300.90 |
| | MAX. | 391.93 | 336.99 | 344.32 | 391.93 | 329.67 | 377.28 |
| | MIN. | 296.70 | 223.44 | 278.38 | 230.76 | 271.06 | 238.09 |
| | RMS | 19.69 | 28.36 | 13.18 | 39.76 | 11.65 | 35.00 |
| | RMS(L) | 17.66 | 26.85 | 9.85 | 38.85 | 8.73 | 34.29 |
| | RMS(H) | 8.71 | 9.12 | 8.76 | 8.48 | 7.71 | 7.01 |
| | RAO | 1.547 | 1.562 | 1.529 | 1.556 | 1.334 | |

Table 6.12 Statistics of the test results in regular wave (wave height=20ft, period=14sec)

| REGULAR WAVE: H=20 FT, T=14 SEC | | | | | | | |
|---------------------------------|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.19 | 0.11 | 0.10 | 0.06 | 0.03 | 0.03 |
| | MAX. | 12.45 | 12.38 | 12.89 | 12.72 | 12.40 | 8.24 |
| | MIN. | -13.89 | -12.75 | -12.97 | -12.60 | -12.61 | -9.56 |
| | RMS | 8.03 | 8.02 | 8.03 | 7.71 | 8.12 | 6.20 |
| SURGE: (FT) | | | | | | | |
| | MEAN | -9.03 | -2.09 | -2.86 | -1.21 | -6.60 | -3.36 |
| | MAX. | 1.00 | 5.29 | 3.14 | 5.76 | 0.82 | 8.72 |
| | MIN. | -18.11 | -9.98 | -8.92 | -9.00 | -14.23 | -12.75 |
| | RMS | 3.74 | 3.40 | 2.63 | 3.24 | 3.14 | 4.64 |
| | RMS(L) | 2.97 | 2.21 | 1.35 | 2.34 | 2.02 | 3.70 |
| | RMS(H) | 2.26 | 2.58 | 2.26 | 2.25 | 2.40 | 2.79 |
| | RAO | 0.281 | 0.322 | 0.281 | 0.292 | 0.296 | |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 1.20 | 0.46 | 1.98 | 1.17 | 1.11 | 0.72 |
| | MAX. | 6.91 | 5.99 | 9.70 | 7.16 | 6.70 | 5.55 |
| | MIN. | -4.36 | -4.75 | -5.20 | -4.56 | -3.90 | -4.24 |
| | RMS | 3.06 | 3.16 | 3.47 | 3.06 | 2.92 | 2.99 |
| | RMS(L) | 0.81 | 0.54 | 1.66 | 0.76 | 0.55 | 0.28 |
| | RMS(H) | 2.96 | 3.12 | 3.05 | 2.96 | 2.86 | 2.98 |
| | RAO | 0.369 | 0.389 | 0.380 | 0.384 | 0.352 | |
| PITCH: DEG | | | | | | | |
| | MEAN | -0.21 | -0.04 | -0.11 | -0.71 | -0.81 | -0.09 |
| | MAX. | 1.41 | 1.36 | 5.17 | 1.13 | 0.90 | 1.10 |
| | MIN. | -1.80 | -1.45 | -5.66 | -2.49 | -2.71 | -1.26 |
| | RMS | 0.89 | 0.92 | 2.54 | 0.94 | 0.96 | 0.62 |
| | RMS(L) | 0.13 | 0.06 | 2.39 | 0.23 | 0.17 | 0.06 |
| | RMS(H) | 0.88 | 0.92 | 0.87 | 0.91 | 0.95 | 0.62 |
| | RAO | 0.110 | 0.115 | 0.108 | 0.118 | 0.117 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1866.98 | | 1544.15 | 1659.70 | 1646.74 | |
| | MAX. | 2139.88 | | 2396.66 | 1859.76 | 1883.11 | |
| | MIN. | 1579.64 | | 443.59 | 1509.61 | 1521.28 | |
| | RMS | 123.91 | | 403.81 | 72.43 | 97.54 | |
| | RMS(L) | 34.46 | | 377.28 | 25.24 | 14.20 | |
| | RMS(H) | 119.02 | | 143.97 | 67.89 | 96.50 | |
| | RAO | 14.822 | 0.000 | 17.929 | 8.805 | 11.884 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1852.62 | | 1448.82 | 1574.08 | 1632.75 | |
| | MAX. | 2105.61 | | 2226.85 | 1721.13 | 1814.66 | |
| | MIN. | 1662.25 | | 602.32 | 1444.03 | 1478.66 | |
| | RMS | 117.10 | | 320.03 | 62.26 | 76.68 | |
| | RMS(L) | 31.07 | | 293.60 | 20.22 | 12.80 | |
| | RMS(H) | 112.90 | | 127.34 | 58.88 | 75.60 | |
| | RAO | 14.060 | 0.000 | 15.858 | 7.637 | 9.310 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 364.23 | 281.71 | 330.58 | 325.19 | 323.82 | 288.36 |
| | MAX. | 443.22 | 329.67 | 377.28 | 369.96 | 373.62 | 340.65 |
| | MIN. | 307.69 | 238.09 | 285.71 | 278.38 | 271.06 | 219.78 |
| | RMS | 24.71 | 21.29 | 20.66 | 21.70 | 21.56 | 25.07 |
| | RMS(L) | 15.61 | 10.11 | 8.87 | 12.14 | 12.73 | 16.79 |
| | RMS(H) | 19.15 | 18.74 | 18.66 | 17.99 | 17.40 | 18.62 |
| | RAO | 2.385 | 2.337 | 2.324 | 2.333 | 2.143 | |

Table 6.13 Statistics of the test results in regular wave (wave height=20ft, period=16sec)

| REGULAR WAVE: H=20 FT, T=16 SEC | | | | | | | |
|---------------------------------|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.18 | 0.10 | 0.11 | 0.14 | -0.05 | -0.01 |
| | MAX. | 13.86 | 13.03 | 13.20 | 12.60 | 13.19 | 12.88 |
| | MIN. | -13.33 | -13.55 | -14.72 | -12.53 | -13.22 | -14.85 |
| | RMS | 8.32 | 8.48 | 8.59 | 8.32 | 8.63 | 8.43 |
| SURGE: (FT) | | | | | | | |
| | MEAN | -5.17 | -3.67 | -4.07 | -1.28 | -6.83 | -9.54 |
| | MAX. | 1.29 | 7.82 | 4.70 | 5.14 | -1.03 | 3.70 |
| | MIN. | -11.68 | -11.58 | -12.52 | -7.86 | -13.44 | -19.76 |
| | RMS | 3.38 | 4.40 | 3.57 | 3.36 | 3.33 | 4.81 |
| | RMS(L) | 0.99 | 2.59 | 2.08 | 0.91 | 0.88 | 3.07 |
| | RMS(H) | 3.24 | 3.56 | 2.91 | 3.24 | 3.21 | 3.70 |
| | RAO | 0.389 | 0.420 | 0.339 | 0.389 | 0.372 | |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 0.56 | 0.41 | 2.33 | 0.54 | 0.40 | 1.05 |
| | MAX. | 6.95 | 6.80 | 11.43 | 6.85 | 6.88 | 7.21 |
| | MIN. | -5.89 | -5.67 | -6.44 | -5.41 | -5.28 | -4.89 |
| | RMS | 3.97 | 3.90 | 4.15 | 3.85 | 3.75 | 3.80 |
| | RMS(L) | 0.41 | 0.30 | 1.64 | 0.33 | 0.23 | 0.32 |
| | RMS(H) | 3.95 | 3.89 | 3.81 | 3.83 | 3.75 | 3.79 |
| | RAO | 0.475 | 0.459 | 0.444 | 0.460 | 0.435 | |
| PITCH: DEG | | | | | | | |
| | MEAN | -0.19 | -0.01 | -0.12 | -0.66 | -0.75 | -0.09 |
| | MAX. | 1.21 | 1.37 | 5.68 | 1.06 | 0.86 | 1.38 |
| | MIN. | -1.64 | -1.41 | -6.25 | -2.13 | -2.35 | -1.60 |
| | RMS | 0.82 | 0.89 | 3.18 | 0.86 | 0.89 | 0.84 |
| | RMS(L) | 0.08 | 0.06 | 3.07 | 0.15 | 0.14 | 0.05 |
| | RMS(H) | 0.82 | 0.89 | 0.83 | 0.85 | 0.88 | 0.84 |
| | RAO | 0.099 | 0.105 | 0.097 | 0.102 | 0.102 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1869.19 | | 1567.70 | 1650.78 | 1662.90 | |
| | MAX. | 2069.85 | | 2431.68 | 1754.72 | 1844.20 | |
| | MIN. | 1735.26 | | 575.87 | 1529.06 | 1540.74 | |
| | RMS | 100.75 | | 430.45 | 52.18 | 72.52 | |
| | RMS(L) | 18.05 | | 408.16 | 9.79 | 13.67 | |
| | RMS(H) | 99.12 | | 136.71 | 51.25 | 71.22 | |
| | RAO | 11.913 | 0.000 | 15.915 | 6.160 | 8.253 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1847.41 | | 1475.51 | 1573.77 | 1638.78 | |
| | MAX. | 2032.88 | | 2164.50 | 1672.64 | 1762.70 | |
| | MIN. | 1658.78 | | 681.99 | 1447.49 | 1471.74 | |
| | RMS | 103.43 | | 331.68 | 59.17 | 64.39 | |
| | RMS(L) | 16.88 | | 307.65 | 11.62 | 13.30 | |
| | RMS(H) | 102.04 | | 123.97 | 58.01 | 63.01 | |
| | RAO | 12.264 | 0.000 | 14.432 | 6.972 | 7.301 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 336.00 | 281.54 | 335.42 | 307.36 | 310.00 | 315.75 |
| | MAX. | 384.61 | 333.33 | 391.93 | 355.30 | 358.97 | 373.62 |
| | MIN. | 289.37 | 219.78 | 271.06 | 256.41 | 271.06 | 245.42 |
| | RMS | 26.46 | 26.82 | 25.92 | 25.08 | 23.62 | 28.39 |
| | RMS(L) | 6.80 | 11.25 | 11.42 | 6.13 | 6.28 | 14.74 |
| | RMS(H) | 25.57 | 24.34 | 23.28 | 24.32 | 22.77 | 24.26 |
| | RAO | 3.073 | 2.870 | 2.710 | 2.923 | 2.638 | |

Table 6.14 Statistics of the test results in regular wave (wave height=20ft, period=18sec)

| REGULAR WAVE: H=20 FT, T=18 SEC | | | | | | | |
|---------------------------------|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.06 | 0.03 | -0.03 | 0.05 | -0.09 | -0.14 |
| | MAX. | 11.92 | 11.70 | 11.54 | 12.54 | 11.15 | 11.56 |
| | MIN. | -12.73 | -13.25 | -12.68 | -13.26 | -12.59 | -13.93 |
| | RMS | 8.46 | 8.34 | 8.37 | 8.39 | 8.53 | 8.60 |
| SURGE: (FT) | | | | | | | |
| | MEAN | 2.43 | 2.63 | -3.00 | -1.23 | -3.00 | -1.66 |
| | MAX. | 16.92 | 16.47 | 3.42 | 6.30 | 6.54 | 7.89 |
| | MIN. | -9.74 | -9.74 | -9.03 | -7.05 | -9.41 | -12.35 |
| | RMS | 5.83 | 6.08 | 3.46 | 3.67 | 3.93 | 4.49 |
| | RMS(L) | 4.39 | 4.49 | 0.70 | 0.68 | 1.41 | 1.79 |
| | RMS(H) | 3.83 | 4.11 | 3.38 | 3.60 | 3.67 | 4.11 |
| | RAO | 0.453 | 0.493 | 0.404 | 0.429 | 0.430 | |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 0.41 | 0.29 | 2.34 | 0.49 | 0.44 | 0.30 |
| | MAX. | 7.49 | 7.18 | 10.06 | 7.65 | 7.47 | 7.57 |
| | MIN. | -6.75 | -6.47 | -5.18 | -5.99 | -6.09 | -6.51 |
| | RMS | 4.57 | 4.37 | 4.43 | 4.32 | 4.40 | 4.38 |
| | RMS(L) | 0.31 | 0.19 | 0.93 | 0.28 | 0.20 | 0.27 |
| | RMS(H) | 4.56 | 4.37 | 4.33 | 4.31 | 4.40 | 4.37 |
| | RAO | 0.539 | 0.524 | 0.517 | 0.514 | 0.516 | |
| PITCH: DEG | | | | | | | |
| | MEAN | 0.06 | -0.07 | -0.07 | -0.01 | -0.14 | 0.02 |
| | MAX. | 1.31 | 1.25 | 1.70 | 1.33 | 1.22 | 1.41 |
| | MIN. | -1.13 | -1.33 | -1.61 | -1.23 | -1.44 | -1.31 |
| | RMS | 0.74 | 0.78 | 0.81 | 0.71 | 0.71 | 0.75 |
| | RMS(L) | 0.06 | 0.04 | 0.26 | 0.08 | 0.10 | 0.05 |
| | RMS(H) | 0.73 | 0.78 | 0.77 | 0.70 | 0.70 | 0.74 |
| | RAO | 0.086 | 0.094 | 0.092 | 0.083 | 0.082 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1881.15 | | 1562.47 | 1676.31 | 1628.43 | |
| | MAX. | 1992.04 | | 1766.39 | 1743.05 | 1715.81 | |
| | MIN. | 1750.83 | | 1307.30 | 1599.09 | 1548.52 | |
| | RMS | 65.17 | | 89.08 | 34.19 | 40.74 | |
| | RMS(L) | 11.43 | | 33.84 | 8.43 | 9.99 | |
| | RMS(H) | 64.16 | | 82.40 | 33.14 | 39.50 | |
| | RAO | 7.584 | 0.000 | 9.845 | 3.950 | 4.631 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1852.35 | | 1480.16 | 1587.60 | 1640.42 | |
| | MAX. | 1998.24 | | 1710.74 | 1669.17 | 1752.31 | |
| | MIN. | 1696.89 | | 1205.02 | 1520.23 | 1551.41 | |
| | RMS | 82.94 | | 109.04 | 36.29 | 53.24 | |
| | RMS(L) | 12.00 | | 37.70 | 8.81 | 8.72 | |
| | RMS(H) | 82.07 | | 102.30 | 35.21 | 52.52 | |
| | RAO | 9.701 | 0.000 | 12.222 | 4.197 | 6.157 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 312.12 | 276.28 | 330.36 | 294.98 | 287.64 | 271.06 |
| | MAX. | 395.60 | 347.98 | 377.28 | 340.65 | 336.99 | 329.67 |
| | MIN. | 223.44 | 201.46 | 278.38 | 241.75 | 223.44 | 208.79 |
| | RMS | 40.27 | 33.76 | 26.39 | 28.96 | 28.75 | 29.48 |
| | RMS(L) | 27.53 | 20.28 | 5.83 | 4.51 | 8.02 | 8.59 |
| | RMS(H) | 29.39 | 26.99 | 25.73 | 28.61 | 27.61 | 28.20 |
| | RAO | 3.474 | 3.236 | 3.074 | 3.410 | 3.237 | |

Table 6.15 Statistics of the test results in 10 year storm ($H_s=20\text{ft}$, $T_p=11\text{sec}$, JONSWAP spectrum, over-shooting parameter=2)

| IRREGULAR WAVE: $H_s=20\text{ FT}$, $T_p=11\text{ SEC}$, JONSWAP ($\text{GAMMA}=2$) | | | | | | | |
|---|--------|---------|--------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| | MEAN | 0.33 | 0.29 | 0.25 | -0.12 | 0.21 | 0.24 |
| | MAX. | 26.65 | 22.86 | 23.90 | 22.29 | 21.69 | 19.92 |
| | MIN. | -18.65 | -19.89 | -17.58 | -20.52 | -18.76 | -16.59 |
| | RMS | 5.57 | 5.52 | 5.52 | 5.40 | 5.49 | 5.23 |
| SURGE: (FT) | | | | | | | |
| | MEAN | -6.16 | -2.58 | -3.22 | -12.17 | -4.62 | -9.48 |
| | MAX. | 15.68 | 15.19 | 12.19 | 8.30 | 19.39 | 15.84 |
| | MIN. | -34.96 | -18.52 | -19.20 | -35.21 | -30.65 | -42.40 |
| | RMS | 8.37 | 6.18 | 5.39 | 7.90 | 8.16 | 10.40 |
| | RMS(L) | 8.32 | 6.12 | 5.33 | 7.86 | 8.12 | 10.35 |
| | RMS(H) | 0.84 | 0.82 | 0.78 | 0.87 | 0.74 | 0.97 |
| HEAVE: (FT) | | | | | | | |
| | MEAN | 1.09 | 0.33 | 0.75 | 0.83 | 0.96 | 1.26 |
| | MAX. | 13.68 | 10.24 | 11.95 | 12.22 | 10.65 | 14.75 |
| | MIN. | -9.26 | -7.22 | -8.15 | -9.71 | -6.61 | -8.84 |
| | RMS | 4.04 | 2.82 | 3.39 | 4.30 | 3.08 | 3.93 |
| | RMS(L) | 3.93 | 2.63 | 3.24 | 4.19 | 2.92 | 3.81 |
| | RMS(H) | 0.96 | 1.02 | 0.99 | 0.94 | 1.00 | 0.95 |
| PITCH: DEG) | | | | | | | |
| | MEAN | -0.06 | -0.11 | 0.05 | -0.10 | -0.40 | |
| | MAX. | 3.55 | 2.17 | 3.27 | 3.31 | 2.48 | |
| | MIN. | -3.64 | -2.44 | -3.19 | -4.29 | -3.98 | |
| | RMS | 1.36 | 0.73 | 1.10 | 1.18 | 1.02 | |
| | RMS(L) | 1.29 | 0.58 | 1.02 | 1.10 | 0.92 | |
| | RMS(H) | 0.44 | 0.44 | 0.42 | 0.43 | 0.42 | |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 1871.24 | | 1498.54 | 1666.66 | 1656.25 | |
| | MAX. | 2626.21 | | 2182.68 | 2314.96 | 2116.54 | |
| | MIN. | 1132.22 | | 665.36 | 929.91 | 1233.38 | |
| | RMS | 255.59 | | 222.31 | 216.38 | 140.20 | |
| | RMS(L) | 232.16 | | 196.13 | 209.53 | 121.51 | |
| | RMS(H) | 106.89 | | 104.66 | 54.03 | 69.94 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| | MEAN | 1846.19 | | 1416.25 | 1566.65 | 1645.38 | |
| | MAX. | 2472.78 | | 1946.28 | 2098.69 | 2012.09 | |
| | MIN. | 1256.98 | | 799.76 | 976.41 | 1274.30 | |
| | RMS | 196.26 | | 175.54 | 187.46 | 110.16 | |
| | RMS(L) | 177.28 | | 153.12 | 182.54 | 96.55 | |
| | RMS(H) | 84.22 | | 85.85 | 42.68 | 53.04 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| | MEAN | 354.42 | 300.00 | 326.30 | 322.04 | 297.25 | 311.19 |
| | MAX. | 743.58 | 391.93 | 428.56 | 512.81 | 545.78 | 677.64 |
| | MIN. | 216.11 | 212.45 | 241.75 | 186.81 | 164.83 | 164.83 |
| | RMS | 65.36 | 32.31 | 32.16 | 48.94 | 50.15 | 69.42 |
| | RMS(L) | 64.64 | 31.66 | 31.52 | 48.27 | 49.69 | 69.03 |
| | RMS(H) | 9.69 | 6.45 | 6.39 | 8.02 | 6.78 | 7.34 |

Table 6.16 Statistics of the test results in 100 year storm ($H_s=39\text{ft}$, $T_p=14.1\text{sec}$, JONSWAP spectrum, over-shooting parameter=2)

| IRREGULAR WAVE: $H_s=39\text{ FT}$, $T_p=14.1\text{ SEC}$, JONSWAP ($\text{GAMMA}=2$) | | | | | | | |
|---|--|---------|---------|---------|------------|--------------|-------------|
| | | U JOINT | FIXED | DAMPED | HOUR GLASS | SPRING CONN. | WITHOUT C.C |
| WAVE ELEV. 2: (FT) | | | | | | | |
| MEAN | | -0.08 | -0.05 | -0.07 | -0.31 | -0.20 | -0.13 |
| MAX. | | 46.64 | 51.07 | 48.74 | 48.59 | 45.47 | 48.41 |
| MIN. | | -41.59 | -41.28 | -40.34 | -42.15 | -41.68 | -40.00 |
| RMS | | 10.82 | 10.73 | 10.73 | 10.90 | 10.96 | 11.11 |
| SURGE: (FT) | | | | | | | |
| MEAN | | -17.70 | -11.62 | -12.12 | -17.59 | -19.56 | -16.03 |
| MAX. | | 29.99 | 25.49 | 33.52 | 29.86 | 38.13 | 62.41 |
| MIN. | | -55.86 | -51.31 | -55.08 | -56.78 | -65.94 | -65.65 |
| RMS | | 13.90 | 12.57 | 13.03 | 13.57 | 15.69 | 20.73 |
| RMS(L) | | 13.57 | 12.16 | 12.70 | 13.22 | 15.39 | 17.87 |
| RMS(H) | | 3.04 | 3.18 | 2.94 | 3.03 | 3.01 | 10.51 |
| HEAVE: (FT) | | | | | | | |
| MEAN | | 1.86 | 0.70 | 3.13 | 2.16 | 2.12 | 4.25 |
| MAX. | | 22.41 | 26.65 | 30.26 | 27.22 | 30.89 | 38.83 |
| MIN. | | -19.52 | -19.29 | -18.97 | -13.64 | -12.54 | -15.14 |
| RMS | | 5.91 | 5.96 | 6.82 | 6.37 | 5.38 | 6.28 |
| RMS(L) | | 4.58 | 4.59 | 5.64 | 5.13 | 3.86 | 4.73 |
| RMS(H) | | 3.73 | 3.80 | 3.84 | 3.78 | 3.75 | 4.13 |
| PITCH: DEG) | | | | | | | |
| MEAN | | -0.51 | -0.17 | -0.32 | -0.85 | -1.51 | -2.97 |
| MAX. | | 4.15 | 7.12 | 7.11 | 5.51 | 6.02 | 4.06 |
| MIN. | | -8.10 | -6.38 | -8.82 | -9.37 | -13.15 | -22.54 |
| RMS | | 1.60 | 1.44 | 2.36 | 2.31 | 2.89 | 4.64 |
| RMS(L) | | 1.17 | 0.99 | 2.10 | 2.02 | 2.67 | 3.48 |
| RMS(H) | | 1.08 | 1.05 | 1.08 | 1.10 | 1.09 | 3.07 |
| JOINT 1 TSN: (KIPS) | | | | | | | |
| MEAN | | 1818.33 | | 1510.56 | 1608.65 | 1694.56 | |
| MAX. | | 2820.74 | | 2704.02 | 2688.46 | 2474.47 | |
| MIN. | | 494.17 | | 23.41 | 350.22 | 894.90 | |
| RMS | | 332.22 | | 423.97 | 313.30 | 260.63 | |
| RMS(L) | | 288.06 | | 376.21 | 288.40 | 224.11 | |
| RMS(H) | | 165.50 | | 195.50 | 122.40 | 133.07 | |
| JOINT 2 TSN: (KIPS) | | | | | | | |
| MEAN | | 1819.27 | | 1425.32 | 1534.13 | 1686.86 | |
| MAX. | | 2753.35 | | 2528.20 | 2251.10 | 2309.98 | |
| MIN. | | 661.20 | | 103.53 | 636.96 | 820.54 | |
| RMS | | 267.60 | | 348.53 | 236.40 | 211.00 | |
| RMS(L) | | 225.38 | | 299.43 | 217.20 | 177.36 | |
| RMS(H) | | 144.28 | | 178.36 | 93.32 | 114.30 | |
| MOOR 1 TSN: (KIPS) | | | | | | | |
| MEAN | | 465.27 | 346.84 | 398.21 | 406.44 | 404.16 | 474.58 |
| MAX. | | 1424.88 | 1065.92 | 1432.21 | 1336.97 | 1545.76 | 1531.11 |
| MIN. | | 139.19 | 120.88 | 135.53 | 109.89 | 76.92 | 95.24 |
| RMS | | 169.17 | 105.00 | 127.99 | 141.13 | 171.64 | 200.50 |
| RMS(L) | | 156.74 | 96.81 | 119.59 | 130.92 | 162.08 | 189.68 |
| RMS(H) | | 63.65 | 40.65 | 45.61 | 52.72 | 56.50 | 64.99 |

CHAPTER 7 COST ESTIMATE AND SCHEDULE

The cost estimate and fabrication schedule was not completed because the work was stopped by customer order prior to completion of CLIN 0006.

CHAPTER 8 CONCLUSIONS

In this conceptual study, an articulated stable ocean platform (ASOP) was designed with a fuel storage capability of 1 million barrels. The platform was also designed to support a topside up to 12,000 kips in total weight. In the hull design, more than eighty percent of the volume for fuel storage was designed to be pressure compensated tanks to reduce the structural size and steel weight. In addition, by pumping at a fixed ratio between pressure compensated and uncompensated tanks, the draft of the platform would remain unchanged at any loading condition without adjusting the ballast. This greatly simplified the operations and allowed the platform to continue other activities while loading and off-loading, such as oil drilling and/or production, which has high restrictions in draft changes.

The study shows that the ASOP has adequate stability and satisfies the stability requirement of the certifying authorities (US Coast Guard, American Bureau of Shipping). Both numerical analysis and model test showed that the ASOP offers exceptional motion response characteristics in all its degrees of freedom. This is evident from Table 8.1 which illustrates the ASOP motions in comparison with a typical surface type production and storage vessel. In terms of platform motion response, the ASOP is capable of operating in more severe weather conditions than a conventional surface vessel type platform.

In the numerical analysis, the articulation of the buoys complicated the analysis by allowing relative motion between the buoys and the hull. Instead of traditional single rigid body analysis for the floating platform, a seven body (six buoys and the hull) coupled analysis was needed for the ASOP. The study showed that the computer software MOSES was capable of performing multi-body analysis for the ASOP, and the numerical results in general agreed with the model test. In regular wave analysis, there was very good agreement between numerical and model test results in heave motion, universal joint force and mooring tension. The surge and pitch motions were slightly over predicted numerically but on the conservative side. In random wave analysis, the wave frequency motions and forces of the ASOP agreed with the model test results but there was a discrepancy in the slow drift motions. Numerical tools need to be improved in this respect to more accurately predict the nonlinear wave forces.

Both numerical analysis and model tests showed that the articulated buoys have no clear advantage over fixed buoys in the global motion of the ASOP. The original thought that

articulation reduced the wave forces transmitted to the hull and hence reduced the motion of the ASOP was not supported by analysis or model test. The study showed that the majority of the wave forces were acting on the main hull itself which has more than 90 percent of the total displaced volume. Therefore, the reduction of forces by using articulation did not significantly improve the motion of the platform. Furthermore, the analysis and model test showed that compared to the fixed buoy case, using articulations increased the slow drift motions of the ASOP in random waves. The large rotational motion of the buoys created more nonlinear forces at the joints and caused large drift motions. The study also indicated that using spring connected buoys, or changing the buoy shape could further reduce the force transmitted from the buoys to the hull, but their influence on the motion of the platform and mooring line tension was insignificant.

The study also indicated that the introduction of articulations complicated the hydrostatic stability of the platform. Figure 8.1 is a comparison of stability of the ASOP between articulated and fixed buoys. The righting moment of the ASOP was greatly reduced due to the unique behavior of the articulated buoys. In order to have adequate stability, a larger initial stability (metacenter height) was required. Also, the loss of a buoy due to universal joint failure or complete buoyancy loss may cause serious stability problems. Damaged stability was the governing factor in determination of the size of the articulated buoys.

In conclusion, this conceptual study indicated that the fuel storage ASOP is a viable concept. Its large storage capability and exceptional motion characteristics allow many applications both in civil and military purpose. However, the introduction of articulation has no clear benefit over fixed buoys (simple columns) in reducing the motion of the platform. Therefore, the same platform with fixed columns instead of articulated buoys could be a more practical design. Figure 8.2 shows a similar platform to the ASOP with fixed columns instead of articulated buoys. This storage platform concept shows merit and should be developed further.

Although the articulation does not show clear advantage in the fuel storage ASOP, it may improve the motion of a more mobile catamaran type ASOP (non-storage vessel). Figure 8.3 is a concept drawing of the platform with articulated buoys (the catamaran ASOP). Unlike the storage ASOP, the displacement of the buoys has a much higher percentage in the total displacement and the wave forces on the buoys are significant. Therefore, reduction of the wave forces transmitted from buoys using articulation could possibly effectively improve the motion of the platform. Evaluation of the catamaran version of the

ASOP concept is not in the scope of this study, however this concept may be worth investigating further.

Table 8.1 Comparison of standard deviation of motion in 100 year storm

(Significant wave height = 39 ft)

| | SURGE (FT) | HEAVE (FT) | PITCH (DEG) |
|-------|---------------|---------------|----------------|
| ASOP | 13.90 | 5.90 | 1.9 |
| FPSO* | 29.53 | 11.15 | 4.1 |

* A turret moored 102,500 DWT tanker system. Test results are from Applied Ocean Research 0141-1187/92

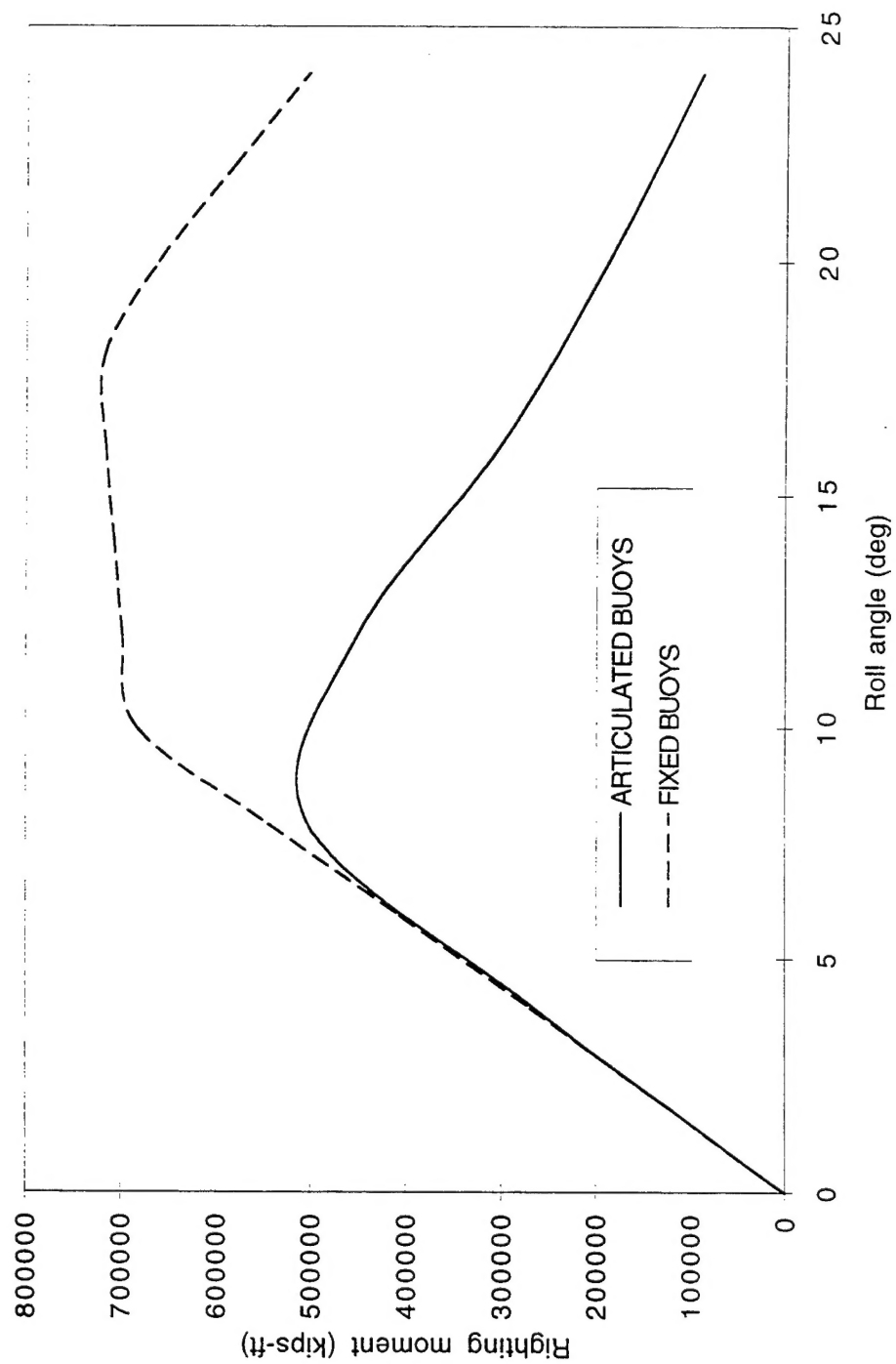


Figure 8.1 Righting moment of the ASOP with fixed buoys and articulated buoys

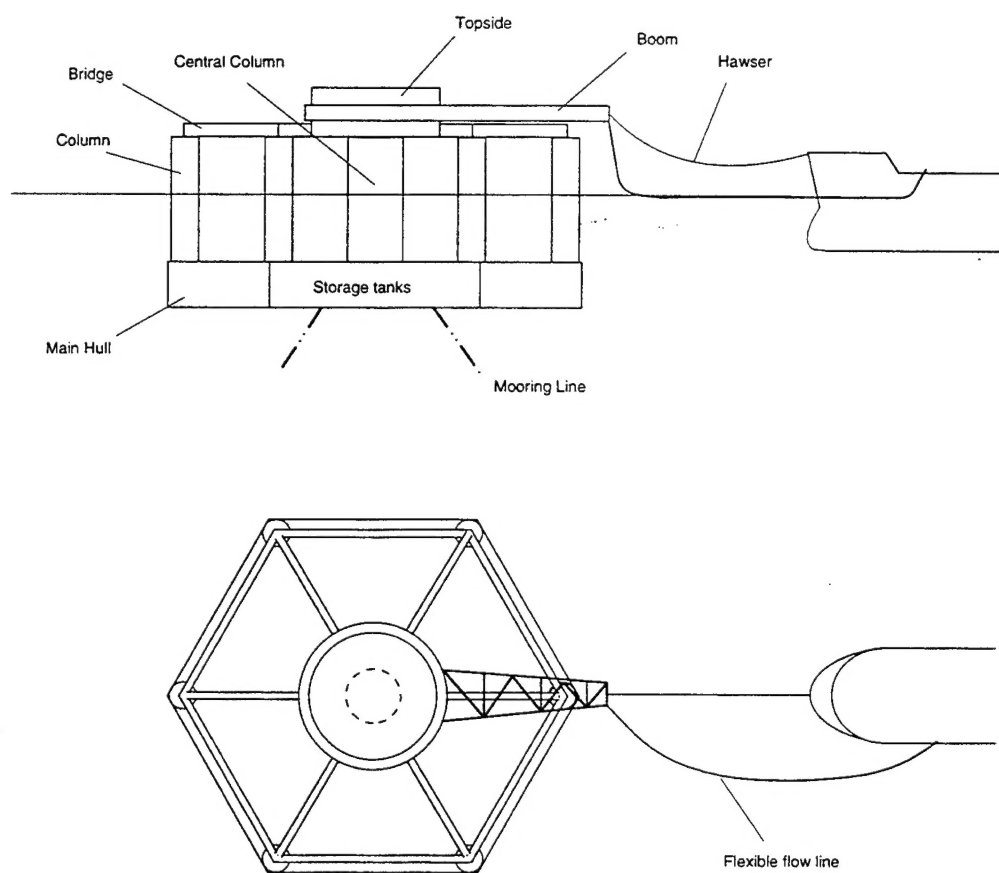


Figure 8.2 A column stabilized storage and production platform

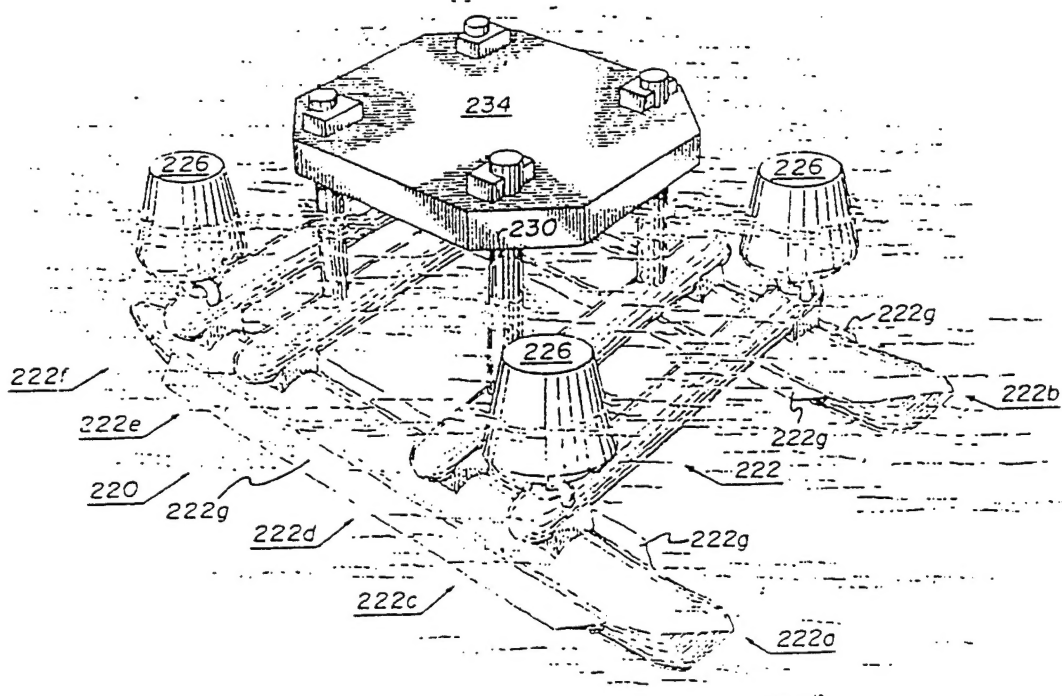


Figure 8.3 A catamaran type ASOP